

**Burmuin aktibitatearen aldaketak
helduen hizkuntza ikasketan,
magnetoentzefalografia bidez neurtuta**

**Changes in brain activity during
language learning in adults measured by
magnetoencephalography**



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alfa frekuentzia ikusi nuelako, ezer ulertu gabe ere nerekin batera alaitu zerate. Eta nerekin ospatu dituzue ospatu beharrekoak. Ta lanean momentu gogorak bizi izan ditudanean ere, ulertuta edo ulertu gabe, nere babes handiena izan zerate. Ez dakit zer egingo dudan nere bizitzarekin behin tesia amaituta, baina espero det bizitza hori zuekin konpartitzeko aukera izatea. Zoragarriak zarete!

Abstract

The main goal of this thesis was to characterize language-related short-term learning changes in the adult brain. Previous studies have mainly used longitudinal and cross-sectional designs and therefore they captured brain responses of already consolidated rules. On the other hand, studies that used on line or lab training, and therefore captured short-term changes, were conducted with EEG and provided no source correlates related to these changes. However, short-term and long-term learning seem to elicit different plastic changes; hence, the anatomical-correlates of the MEG experiments carried out in this thesis provide useful information to better understand which plastic changes occur in short-term learning. Subsets of natural languages (miniature languages) were used in two of the experiments in order to study short-term changes in grammar learning and sentence comprehension. It was hypothesized that miniature languages allow capturing language-related changes without the need of long-term training. Behavioural results indicate that rapid grammar and vocabulary learning can occur in adults. Moreover, the rapid grammar learning was accompanied by changes in the evoked response field (ERF) measured in MEG. ERFs before training showed no violation control effects, but the effect appeared with training. Furthermore, with training the brain network supporting the effect started to approximate the network in L1. In addition, sentence comprehension elicited large oscillatory power differences between native and newly-learned language. Nonetheless, no strong effect of vocabulary learning was found in the oscillatory analysis, but only differences between native vs. newly-learned language. The third experiment was a memory task in the participants' native language, and aimed to provide a better understanding of the oscillatory mechanisms underlying memory retrieval with closed or open eyes. The oscillatory analysis revealed modulations of the tau rhythm, distinct from the alpha rhythm, due to remembered and forgotten items. These results indicate that when focusing in a short-period of time, oscillatory modulations could be easier to identify and that might be the reason why the sentence comprehension experiment did not show an oscillatory effect of learning. In summary, this thesis opens a door to a new way of studying L2 learning, providing anatomical correlates of short-term language-related brain changes.

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Euskarazko bertsioa

Sarrera

Luzaroan ikertua izan bada ere, gizakien burmuinak misterio bat izaten jarraitzen du. Bide luzea dugu bere zirkuiteriak hizkuntza bezalako ekintza liluragarrietan nola amaitzen duen ulertu arte. Eta misterioaren misterioa, umeez arazorik gabe haien ama hizkuntza ikasten duten bitartean, bigarren hizkuntza bat ikasi nahi duten helduek ez dute hain emaitza arrakastatsua erakusten. Zer prozesu kognitibo gertatzen dira burmuin heldu batean hizkuntza bat ikasten duen bitartean?

Egungo neuroirudi teknikek bigarren hizkuntza (H2) bat prozesatzen dugun bitartean burmuineko aktibitatea grabatzea ahalbidetzen digute. Teknika hauek ekarritako aurrerapenengatik interesa handitu da H2-ren ikasketarekin erlacionatutako burmuin aktibitatearen aldaketak neurtzeko neuroirudi ikerketetan. 1 irudiak neuroirudi teknika arruntak erabiltzen dituzten H2-ren ikasketaren gaineko ikerketak laburtzen ditu, ikasketa mota ezberdinen arabera: momentuko ikasketa ikertzetik urteetan zehar hizkuntza bat ikasi dutenen talde konparaketak egiten dituzten ikerketak arte. Koloreek ariketa ezberdinak adierazten dituzte (mintzamina, ulermena, gramatika epaiketa). Taula honek argi erakusten du bigarren hizkuntzaren jabetzean (Second Language Acquisition, SLA) domeinu ezberdinetan ikertzeko lan oparoa dagoen arren, ikerketa gehienak, teknika ezberdinak erabiliz, ikasketa prozesuaren emaitzetan jarri dutela arreta eta ez ikasketa prozesuan beran.

Tesi honek H2-ren ikasketa bitartean gertatzen diren burmuin aldaketak ikertzen ditu magnetoentzefalografia (MEG) bidez, epe motzeko aldaketetan arreta jarritz. Aldaketa hauek ikertzeko, tesi honek esperimendu multzoa aurkezten du non partaideak laborategian trebatuak izan ziren eta seinale magnetikoak trebakuntza honen aurretik eta ondoren jaso ziren (laborategiko trebakuntza). Gainera, esperimenduetako batean seinale magnetikoak trebakuntza *bitartean* jaso ziren ere (momentuko trebakuntza). Luzetarako eta zehar-sekzio ikerketekin alderatuta, laborategi (eta momentuko) trebakuntza paradigmek ikasketa gauzatu bezain pronto gertatu diren burmuin aldaketak neurtzeko aukera ematen dute, hau da, burmuin aktibitatean gertatu berri diren aldaketak neurtzeko ahalmena. Bestalde, momentuko trebakuntza paradigmek oroimen hauek sortzen ari diren momentuan gertatzen

	Online Training	Lab Training	Formal Course	Cross-sectional
fMRI			Indefrey et al. 2005 Wang et al. (2003) Sakai et al. 2004	Suh et al. 2007 Yokoyama et al. 2006 Rüschemeyer et al. 2006 Rodríguez-Fornells et al. 2005 Pillai et al. 2004 Xue et al. 2004 Vingerhoets et al. 2003 Perani et al. 2003 Ding et al. 2003 Mathendra et al. 2003 Luke et al. 2002 Hasegawa et al. 2002 Pu et al. 2001 Chee et al. 2001 Hernandez et al. (2000,2001) Chee et al. 1999 Dehaene et al. 197 Illes et al. 1999 Perani et al. (1996,988) Klein et al. 1995
EEG	Davidson and Indefrey (2008,2011)	Batterink and Neville 2013 Morgan-Short et al. 2012 Mueller et al. (2005,2007,2008) Morgan-Short et al. 2010	Bañón et al. 2014 McLaughlin et al. 2010 Osterhout et al. 2006	Proverbio et al. 2012 Foucart and Frenck-Mestre 2011 Zawiszewski et al. 2011 Dowens et al. (2011,2010) Moreno et al. 2010 Guo et al. 2009 Frenck-Mestre et al. 2008 Kotz et al. 2008 Chen et al. 2007 Isel 2007 Rossi et al. 2005 Hahne and Friederici 2001 Hahne 2001 Weber-Fox and Neville 1996
MEG	EXPERIMENT 1	Hultén et al. 2014 Zhang et al. (2000,2001) EXPERIMENT 2	Davidson & Indefrey 2009	

■ Syntactic processing
■ Comprehension
■ Speech production
■ Phonology

1. taula: H2 hiztunen eta ikasleen ikerketen sailkapena. Zutabeek ikasketa mota adierazten dute (momentuko trebakuntza, laborategi trebakuntza, ikastaro formalak (luzetarako ikerketak) eta zehar-sekzio ikerketak). Lerroek neuroirudi teknikak adierazten dituzte (Magnetoentzefalografia (MEG), Elektroentzefalografia (EEG), Erresonantzia Magnetiko Filmagailu funtzionala (fMRI)).

dena ikusteko aukera ematen digute, hizkuntza berria ikasten ari diren bitartean, esaterako. Gaur egun, soilik fonologia laborategi trebakuntzako ikerketek (Zhang et al., 2000, 2001) aurkeztu dituzte epe motzeko aldaketen adierazle anatomikoak. Beste hizkuntza domeinuetan epe motzeko aldaketen adierazle anatomikoek ikertu gabe jarraitzen dute (ikus 1 Taula).

Nire ezagutzaren arabera, tesi honek epe-motzeko gramatika eta hiztegi ikasketekin erlazioatutako aldaketen adierazle anatomikoak dituen lehen ikerketak aurkeztu ditu, eta honekin batera trebakuntza bitartean MEG seinaleak jaso dituen lehenengo ikerketa ere (ikus 1 Taula). Gainera, laborategi edo momentuan trebatu berri den hizkuntzaren eta ama hizkuntzaren burmuin erantzunak alderatzen dituzten aurrengo ikerketak dira.

Hizkuntza ikasketa hasierako faseetan ikertzea, epe motzeko ikasketarekin loturiko burmuin aldaketak jadanik finkatutako arauetatik ezberdintzeko aukeretako bat da. Honen abantaila da saio esperimentaletan trebatutako partaideek ez dutela H2-ren jakintzarik, eta jasotako burmuin erantzunak ezin dira finkatutako oroimenetik eratorri. Bestalde, hasierako gaitasuna (erreferentzia basea) parekatzeko arazoak ekiditen dira.

Gogoan izan behar dugu hizkuntza eta mintzamen prozesuak denbora epe motzean gertatzen direla. Esaldiak segundu gutxi batzuen artean hasi eta bukatzen dira, eta hitzen arteko erlazioak zein gramatika erlazioak esaldi horietan txertatuta daude. Prozesu hauen burmuin erantzunak ulertzeko, hitz solteen erantzunak isolatzeko gauza den irudi teknika behar da eta aldi berean, aktibitate horren adierazle anatomikoak hornitzeko gai den teknika izan behar du. MEG teknika bereziki egokia da egoera honetarako. Lehenik, bere denbora bereizmenak hitz solteei erantzunez 5-10 ms inguruan gertatzen diren potentzial postsinaptikoen frekuentzia baxuko fluktuazioak neurtzeko ahalmena du. Bigarrenik, bere espazio bereizmenak direla eta, neurtutako aktibitatearen adierazle anatomikoak lortu daitezke metodo matematiko egokiak erabiliz. Azkenik, grabaketa saioan zehar partaideek denbora luzez hitz egin eta entzutea baimentzen du, hizkuntza ariketa ezberdinak erabiltzeko aukera emanik.

Tesi honen lehenengo atalak oinarri teoriko, enpiriko eta metodologikoak aurkezten ditu. **1. kapituluak** hizkuntzaren jabetzea ikertzeko erabilitako metodoak aurkezten ditu. Tesi honetan jasotako burmuin aktibitatea eta berau grabatzeko erabilitako MEG teknika **2. kapituluan** azaltzen dira.

Bigarren atalak esperimentuak aurkezten ditu. Lehenengo ikerketek H2-ren jabetzea hasierako faseetan esploratzen dute: **3. kapituluak** gramatika ikaste esperimentua aurkezten du eta **4. kapitulua** hiztegi ikasketa zein esaldi motzen ulermenerako esperimentuan datza. Ondoren, **5. kapituluak** hirugarren esperimentu bat aurkezten du oroimen berreskurapena hobetzearen inguruan, hizkuntza ikasketan ere garrantzitsua dena, oroimen berreskurapenaren mekanismo neuronalak ulertzen lagunduko duelakoan. Kapitulu honen helburua 4. kapituluko emaitzak ulertzen eta interpretatzen laguntzea da.

Azkenik, **6. kapituluak** aurreko emaitza guztiak laburtu eta eztabaida orokorra aurkezten du, emaitza hauek H2-ren ikasketa eta prozesamenduan dagoen oinarri teorikoarekin lotuz.

I. Atala

Oinarri teoriko eta enpirikoa

1. Kapituluia

Hizkuntza ikasketa heldutan

Neurolingistikaren helburua burmuinaren fisiologiak eta antolakuntzak hizkuntza funtzioa nola sortzen duten ulertzea da. Tesi honen asmoa hizkuntza sarearen egitura eta funtzioek epe motzeko hizkuntza jabetzan eta hitzen oroimenean nola laguntzen duten ulertzea da. Kapitulu honek burmuin plastikotasuna, eta hau ikertzeko teknika eta metodoak aurkezten ditu.

1.1 Ikasketa, oroimena eta burmuin plastikotasuna

Gizakiak trebetasun eta portaera forma berriak lortzeko eta ingurune berrietara moldatzeko gaitasuna du. Esperientziak eragindako portaera aldatze prozesua da ikasketa. Oroimena aldiz aldaketaren ondorioa da: moldaketa honen muinean dauden grabaketa iraunkorrak (Anderson, 1995). Biak, ikasketa eta oroimena, nerbio-sisteman gertatzen dira. Hala ere, urte luzez ikasketa eta oroimen prozesuen inguruko ikerkuntza jokabide estudioetan zentratu da ikasketa prozesuaren atzean dauden mekanismoak ondorioztatzeko asmoarekin (Schumann et al., 2004). Bestalde, neurozientzia modernoak portaeran egindako aurkikuntzak burmuinaren aldaketa funtzional eta estrukturalekin erlazionatzen ditu (Diamond and Amso, 2008).

Burmuin plastikotasuna burmuinak bere antolakuntza eta funtzio eskaeren eta esperientziaren baitan moldatzeko duen gaitasuna da (adibidez, hizkuntza jabetze bitartean). Baita alderantziz ere, burmuin plastikotasunak gaitasun kognitiboen garapena ahalbidetzen du (Uylings, 2006). 20. mende hasieran ikerlariak uste zuten aldaketa anatomikoak ezinezkoak zirela garapenaren ondoren (Nieto-Sampedro and Nieto-Díaz, 2005). Hala ere, 50. hamarkada bukaeran Liu and Scott (1958)-k erakutsi zuen nerbio-sistemak gaitasuna zuela funtzionalki eta anatomikoki moldatzeko bizi osoan zehar. Moldaketarako gaitasun hau adinarekin gutxitzen joan zela frogatu da ere (Pascual-Leone et al., 2012). Helduaroko burmuin plastikotasunaren

eztabaida proposamen berri batekin itxi egin zen: gizakien kortexa prozesu neuronal ezberdinez osatua dago eta prozesu bakoitzak berezko plastikotasun profil bat dauka (Uylings, 2006). Prozesu hauek sailkatzeko bi multzo nagusi proposatu ziren: aldaketa anatomiko handiak (adibidez, distantzia luzeko axoien berkableaketa), garapenaren ondoren gertatu ezin direla uste direnak, eta lekuko aldaketak (adibidez, lekuko dendriten eta sinapsien aldakuntzak), helduaroan gelditzen ez direnak. Hala ere, honek ez du esan nahi plastikotasun gaitasuna aldatzen ez denik bizitzan zehar (Pascual-Leone et al., 2012; Uylings, 2006).

Denbora eta espazio eskala ezberdinetan egindako analisiak zenbait portaerarekin erlazionatu daitezkeen plastikotasun profil ezberdinetara izan daitezke sentikorrak, adibidez, eskala espazial txikietan neurona solteen konexio sinaptikoetan gertatzen diren aldaketak neurtu daitezke. Esate baterako, animalietan egindako ikerketetak esperientziak eragindako eremu dendritikoen aldaketetan zentratu izan dira, espazio dendritikoa sinapsi kopuruarekin korrelazioan jartzen den ustean oinarrituta (Kolb et al., 1998). Ikerketa mota honek bi animalia mota konparatu izan ohi ditu: laborategi karioletan dauden animalia taldea eta estimulu oparoagoa duen ingurune batean dagoen animalia taldea. Hil ondoren bi taldeen espazio dendritikoa alderatzen da. Greenoughen taldeak esperientzia aberasgarria izan zuten animalien espazio dendritikoa, kailako animaliekin erkatuz, %20 handiagoa zela aurkitu zuten (Greenough and Volkmar, 1973; Volkmar and Greenough, 1972). Honetaz gain, odol kapilar eta astrozito material gehiago topatu izan dira neuronako sinapsi kopuru igoerekin batera esperientzia aberasgarria izan duten animalia taldeetan (adibidez, Sirevaag and Greenough, 1987).

Antzeko ikerketak erabili izan dira aldaketa dendritikoak eta giza portaera erlazionatzeko. Jacobs et al. (1993)-k arborizazio dendritikoa Wernicke eremuan, hizkuntza sareko eremu garrantzitsua, heziketa mailarekin harreman dagoela aurkitu zuen: heziketa maila zenbat eta altuago izan, are eta arborizazio zabalagoa. Honetaz gain, portaera eta burmuin egituraren arteko harremana ikertu zuten, pertsonen gaitasun funtzionalek egitura neuronalekin korrelatua izango zutelakoan. Emakumeek gizonen baino mintzamen gaitasun handiagoa dutela oinarri hartuz (laburpen baterako ikus Kolb et al., 1996), emakume eta gizonen arborizazioa konparatu zituzten eta emakumeek Wernicke eremuan arborizazio dendritiko zabalagoa dutela topatu zuten.

Hala ere, plastikotasun forma hau hizkuntza jabetzarekin erlazionatzea zaila da. Lehenik eta behin, aldaketa dendritikoek ikasketa isladatzen dutela pentsatzea liluragarria izan daitezkeen arren, ebidentzia gutxi dago honen inguruan (Kolb et al., 1998). Gainera eskala honetako aldaketak ez dira eskuragarriak gizakietan neurtzeko ditugun tekniken bidez. Eskuragarriak izango balira ere, ikasketak

eragindako aldaketak topatzeko burmuinean non begiratu behar den jakitea ez da erraza. Aldaketa dendritiko horiek gizakietan topatuagatik ere, hizkuntza ikasketak hainbeste azpi-prozesu dituzenez gero, zaila izango litzateke aldaketa dendritikoak azpi-prozesu zehatzekin lotzea.

Burmuin eskalako plastikotasuna erraz neurtu daiteke gizakietan, adibidez, materia griseko zabalera gertatzen diren aldaketak (Martensson et al., 2012; Klein et al., 2014) edota burmuineko eremuen arteko konexio funtzionaletan gertatzen diren aldaketak kontuan izanik.(Ghazi Saidi et al., 2013; Price, 2010). Neuroirudi teknikei esker, plastikotasun mota hau eskuragarriago da giza burmuinean in-vivo azterketak egitea ahalbidetzen dutelako, eta beraz, plastikotasunaren eta ikasketaren arteko lotura errazten dute. Hurrengo azpiatalak burmuin osoko plastikotasuna nola neurtu daitekeen eta hizkuntza sareko plastikotasunaz dakiguna azaltzen du.

1.2 Burmuin osoko eskalan plastikotasuna neurtzeko teknikak

Neuroirudi teknikak plastikotasun neuronala sostengatzen duten aldaketa anatomiko eta funtzionalak neurtzeko tresna egokiak dira (Rossini et al., 2003). **Erresonantzia Magnetiko Filmagailua** (Magnetic Resonance Imaging, MRI) zehaztasun anatomikoak neurtzeko bereizketa espazial altuko irudi teknika da. Materia grisaren lodiera edota eremuen arteko fibra traktoak (konexioak) bezalako burmuin egitura adierazleak neurtzeko erabiltzen da. Erresonantzia Magnetiko funtzionala (fMRI) (zeharkako) burmuin aktibitatea neurtzeko ere erabil daiteke, nahiz eta bere denbora bereizketa baxua izan (2 segundu ingurukoa). Segunduen eskalan gertatzen diren aldaketa hemodinamiko neuronalek sortutako burmuin-odol oxigenazio aldaketak neurtzen ditu (Ogawa et al., 1990). Badirudi hizkuntza ariketetan erabiltzen diren burmuin eremuak antzemateko teknika egokia dela (Matthews et al., 2003). Hala ere, esaldi prozesamenduetan gertatzen diren aldaketak neurtzeko denbora bereizketa txiroa eskaintzen du, seinalea segunduetako eskalan neurtzen baita eta hitzak edo esaldiak hori baino azkarrago garatzen dira. Beraz, hizkuntzarekin lotutako burmuin plastikotasuna neurtzeko denbora bereizketa altuago duen teknika egokiago litzateke .

fMRI ez bezala, **Elektroentzefalografia** (EEG) eta **Magnetoentzefalografia** (MEG) denbora bereizketa altuagoko teknikak dira (Schomer and da Silva, 2010; Hämäläinen et al., 1993, hurrenez hurren). Potentzial post-sinaptikoen fluktuazioak neurtzen dituzte, 5-10 ms-ko eskalan gertatzen direlarik (Lopes da Silva, 1991), eta ondorioz, hizkuntzarekin erlazionatutako prozesuen denbora eskalara egokituago

daude. Psikologikoki eta linguistikoki motibatutako diseinu esperimentalekin batera, teknika hauek azpi-prozesu ezberdinen adierazle psikologikoak noiz gertatzen diren ikertzea ahalbidetzen dute: integrazio akustiko-fonologikoa, prozesamendu sintaktiko eta semantikoa, edota integrazio sintaktiko-semantikoa (Friederici, 2011).

EEG eta MEG-en arteko ezberdintasun garrantzitsuenetako bat EEG-k edozein norantzatan sortutako eremu elektrikoak neurtzen dituen bitartean, MEG-ek soilik kortexari tangenzialak diren korranteek sortutako eremu magnetikoak neurtzen dituela da (Hansen et al., 2010). Bestalde, eremu elektrikoen ezaugarri fisikoengatik, EEG seinaleak buruko ehunetatik igarotzean asko degradatzen dira. Eremu magnetikoen ezaugarri fisikoengatik efektu hau mugatua da MEG seinaleetan, bereizketa espaziala hobetzen duelarik (Baillet, 2017). Ondorioz, MEG erabiltzen duten ikerketek neurtutako efektuen kokaleku anatomiko zehatzagoa eskaintzen dute. EEG ikerketek orokorrean ez dituzte uhinen ezaugarrien arduradunak diren burmuin eremuen berri ematen. Tesi honetako esperimentuak MEG teknikaren denbora eta espazio zehaztasunaz baliatzen dira epe motzeko hizkuntza ikasketarekin lotutako plastikotasuna ikertzeko.

Honetaz gain, hiru osagai behar dira gaitasun berri baten jabetzari lotutako plastikotasuna ikertzeko: funtzioa sostengatzen duen burmuin sistema, sistema horren karakterizazio neuronala gaitasun berri batera doitzeko eta, azkenik, portaera eta burmuinaren arteko harremana, behin gaitasun berria martxan denean sistema horren funtzionamendua azaldu dezakeena. MEG teknikaren denbora eta espazio zehaztasunak denbora epe motzeari gertatutako burmuin aktibitatearen adierazle anatomikoa lortzea ahalbidetzen du (Hämäläinen et al., 1993), hizkuntza azpisistemak sostengatzen dituen burmuin sarean deskribapenak emateko tresna egoki bilakatuz. Burmuin osoko eskalan aldaketa funtzionalak neurtzen ditu eta in-vivo azterketak ahalbidetzen ditu, portaera aldaketekin asoziazioak erraztuz. Laburbilduz, MEG hizkuntza ikasketarekin lotutako burmuin osoko eskalan plastikotasuna neurtzeko tresna egokia da (Rossini et al., 2003).

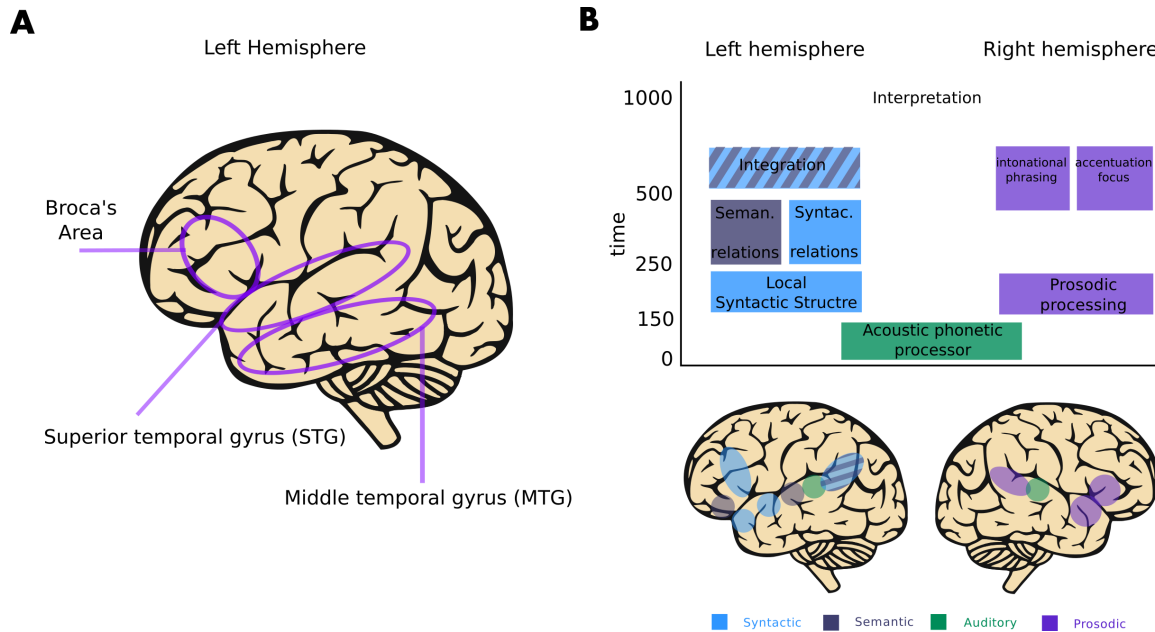
1.3 Hizkuntza sarearen plastikotasuna

Atal honek hizkuntza prozesamenduan nahastuta egon daitezken eremu kortikalak zein eremu hauetan hizkuntzarekin lotutako plastikotasun profilak deskribatzen ditu.

Friederici (2011)-k mintzamenaren ulermenean ematen diren hizkuntzaren azpisistemen kokaleku espaziala eta tenporala proposatzen dituen modelo bat aurkeztu zuen. Modeloa seriean (eta partzialki paraleloan) gertatzen diren

azpi-prozesuez osatuta dago (ikus 1.1 irudia). Friedericiren modeloak ex-vivo eta fMRI ikerketak ditu oinarri hizkuntzaren azpi-funtzioen adierazle anatomikoak proposatzeko. Ikerketa elektrofisiologikoetako ebidentziak azpi-prozesuak gertatzen diren denbora leihoak proposatzeko erabili dira. Modelo honen arabera, lehen analisi akustiko-fonologikoa kortex auditibo eta inguruko eremutan gertatzen da mintzamina hasi eta (gutxi gorabehera) 150 ms-tara (Näätänen and Alho, 1997; Poeppel et al., 1997; Phillips, 2001). Hurrengo fasea hasierako prozesamendu sintaktikoa da, ustez mintzamenaren hasieratik 150 eta 250 ms artean (Friederici and Weissenborn, 2007) ezker-behe-frontal zirkunboluzioan (inferior frontal gyrus, IFG) gertatzen dena (Rüschemeyer et al., 2005; Brauer and Friederici, 2007). Hurrengo fasean harreman sintaktiko eta semantikoak prozesatzen dira, adibidez, aditza eta bere argumentuen arteko harremana (nork nori zer egin dion). Prozesamendu hau 250 eta 500ms artean gertatzen da (ikus Penke et al. (1997); Angrilli et al. (2002) sintaktikorako eta Lau et al. (2008) semantikorako). Harreman sintaktikoak ezker-aurre-tenporal lobuloan eta IFG eremutan prozesatzen dira (Humphries et al., 2006; Friederici et al., 2000, 2003, 2010), harreman semantikoak, ordea, ezker-atze-tenporal lobuloan eta IFG eremutan (Friederici et al., 2003; Obleser and Kotz, 2010). Ondoren, ulermena lortu ahal izateko informazio semantiko eta sintaktikoa elkar-eragin eta integratzen diren fasea dator. Fase hau, ustez, 500 eta 1000 ms artean gertatzen da (Gunter et al., 2000; Kuperberg et al., 2003, 2006) eta ezker-atze-goiko lobulu tenporalean (left posterior superior temporal gyrus, STG) kokatzen da (Grodzinsky and Friederici, 2006). Paraleloki, prozesu fonologiko eta prosodikoak eskuin hemisferioan gertatzen dira. Fonologiari dagokionez, fonemen eta hitzen antzematea 150 eta 250 ms artean gertatzen da (Friederici, 2002). Prosodiari dagokionez, azentu eta doinu prozesuak 500 ms inguruan gertatuko lirateke (Steinhauer et al., 1999).

Hagoort (2016)-ek beste modelo bat proposatu zuen hizkuntza prozesamendurako hiru osagai nagusitan oinarrituta: Oroimen, bateratze eta finkatze modelo (Memory, Unification and Consolidation model, MUC) (ikus 1.2 irudia). Kortex tenporaleko eremuek oroimen osagaia sostengatzen dute (Hagoort, 2003, 2005, 2009), hau da, oroimenean finkatutako jakintza linguistikoaren irudikapenak (Davis and Gaskell, 2009). Jakintza motaren arabera, kortex tenporaleko eremu ezberdinek hartuko dute parte. Bateratze osagaia eremu frontaletan sostengatzen da (Hagoort and Indefrey, 2014), eta bertan oroimenetik ateratako elementuak forma berrietan konbinatzen dira (Hagoort, 2005). Eremu frontalez gain, bateratze prozesu ezberdinek, semantikoa, fonologikoa eta sintaktikoa adibidez, bestelako burmuin eremuak erabiltzen dituzte. Azkenik, kontrol osagaiak hizkuntza egokia aukeratzen du harreman sozialen eskakizunak betetzeko. Ustez, kortex aurre-frontal dortsolateral da kontrol osagaiaren nukleo garrantzitsuena (Kristensen et al., 2013).

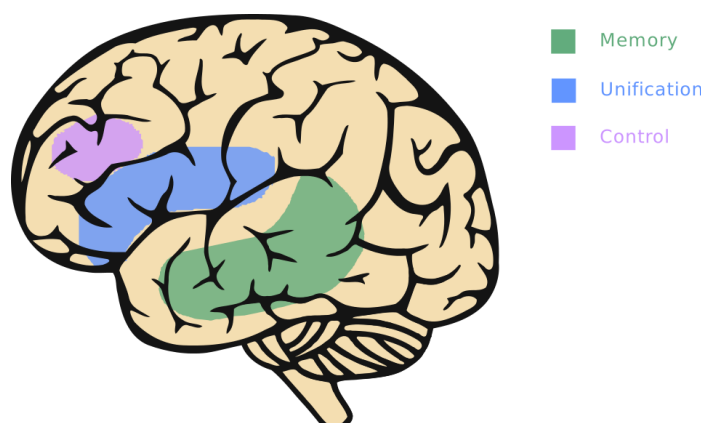


1.1. irudia: Mintzamenaren ulermen modelo bat. A panelak hizkuntza sarearen eremuak izendatzen ditu. B panelak azpiprozesu ezberdinak 'noiz' eta 'non' gertatzen diren azaltzen du eskematikoki (Friederici, 2011, -tik moldatuta).

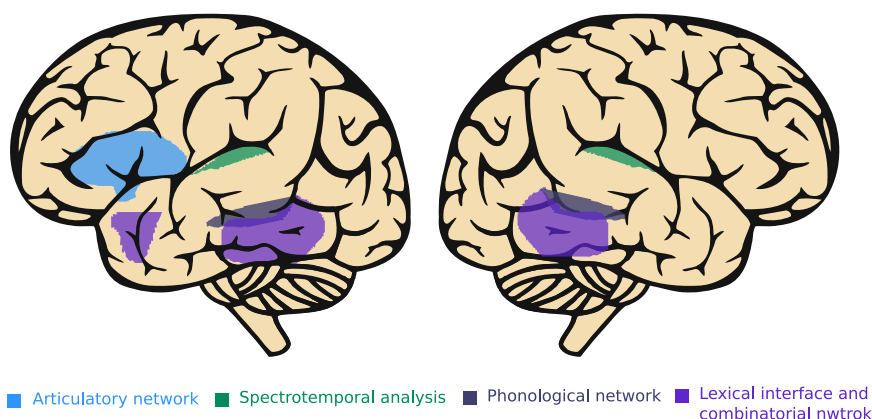
Bi modelo hauek modelo ezberdinek hizkuntza prozesamendua azpistema ezberdinetan banatzen duten adibide dira. Bi modeloen ezaugarri komuna hizkuntza prozesamendua azpistema ezberdinetan banatzea eta azpistema bakoitzak burmuin eremu batean sostengatzea da, Sanderren proposamenarekin bat eginik (Sanders et al., 2008). Garapenaren periodo batzuetan plastikotasun aukerak beste batzuetan baino altuagoak direla jakina da (Knudsen, 2004). Zilles-en arabera, kortexeko eremuek plastikotasun profil ezberdina dute (Zilles, 1978), ondorioz, ikasteko gaitasuna desberdina izan daiteke hizkuntza azpistemetan (Uylings, 2006). Esate baterako, H2 jabetzan geroratzek semantikan efektu minimoak dituzten bitartean, prozesamendu sintaktiko eta fonologikoetan gabeziak sortzen dituztela proposatu izan da (Sanders et al., 2008).

Modeloen artean ezberdintasun anatomiko eta funtzionalak dauden arren, eremu amankomunak ere aurkitzen dira; haien artean ezker lobulu tenporala eta ezker IFGa. Eremu hauek beste hizkuntza prozesamendu modelotan ere aurki daitezke, Hickok eta Poeppelk proposatutakoan adibidez (Hickok and Poeppel, 2007).

Kanal paralelotan inplementatzen diren lexikorako sarbide ugari daudela proposatzen du modelo honek. Modelo honen arabera, segida bentralak mintzamenaren seinaleak ulermenerako prozesatzen ditu (mintzamenaren antzematea), aldiz, segida dorsalak mintzamenaren seinale akustikoak irudikapen artikulatorioetara itzultzen ditu (ikus 1.3 irudia). Modelo honen arabera, sarrera



1.2. irudia: Hizkuntza prozesamenduaren MUC modeloa (Hagoort, 2016).



1.3. irudia: Hickok eta Poeppelen modeloa hizkuntza prozesamendurako (Hickok and Poeppel, 2007).

akustikoaren analisi espekro-tenporala bi hemisferioetako goi-zirkunboluzio tenporaleko (superior temporal gyrus, STG) azalera dorstalaren esku dagoela proposatzen du. Prozesu fonologikoak goi-zisura tenporalaren (superior temporal sulcus, STS) atzeko erdian gertatzen dira. Lobulu tenporalaren atzeko erdi eta behe eremuak, informazio fonologiko eta semantikoen loturan sostengu dira, eta aurreko eremuak, aldiz, bateratze prozesuan kargu dira. Sare artikulatarioa ezker IFG eta eremu premotore dortsalean kokatuta dago.

Hizkuntza ikasketak sortutako aldaketa funtzionalak IFGen eta ezker lobulu tenporalean topatu dira (Indefrey, 2006). Adibidez, Holandesa ikasten ari ziren txinatarrak ikastaroa hasi eta hiru, sei eta bederatzi hilabetetara izan ziren aztertuak (Indefrey et al., 2005). Partaideek esaldiak entzun eta pantailako irudiarekin bat egiten zuen edo ez erantzun behar zuten beraien burmuinaren irudiak MRI bitartez hartzen ziren bitartean. Esaldiak entzuten IFG zuen BOLD erantzuna aldatu egin zen hiru saioetan zehar. Beste ikerketa batek erakutsi du IFGren BOLD erantzuna

aldatu egiten dela aditzen jokatzeari bi hilabeteko trebakuntza izan ondoren (Sakai et al., 2004). Partaideek aditzaren erroa jasotzen zuten eta honen iragana sortu behar zuten. IFGn neurtutako BOLD seinalea trebakuntzaren ondoren estatistikoki altuagoa zela topatu zuten. Gainera, trebakuntza ondorengo seinaleak ariketaren emaitzekin positiboki korrelatzen zuten. Jarraipen ikerketa batean, ariketa berdina erabili zuten Ingelera sei urtez ikasten ibilitako partaideekin (Tatsuno and Sakai, 2005). Kasu honetan, IFGn neurtutako BOLD seinalea ahulagoa zen ariketa ondo egiten zuten partaideetan. Kontrako patroi honek ariketa egiteko behar den esfortzua irudikatu dezakeela proposatu izan da (Indefrey, 2006): Hasierako ikasleek esfortzu gehiago behar dute ariketa burutzeko eta urteetako praktikaren ondoren, ariketa bera errazagoa bilakatzen da.

Lobulu tenporaleko aldaketa funtzionalei dagokienez, H2 erdizko maila duten ikasleek BOLD seinale ahulagoa dute ezker atze-zirkunboluzio tenporalean eta bi hemisferiotako polo tenporalean (Perani et al., 1996). Hau ordea ezberdina da maila altuko ikasleetan, hauen BOLD seinaleak ez du diferentziarik erakusten H1 eta H2 entzuterakoan (Indefrey, 2006). Luzetarako ikerketa batean, Holandesa ikasten ari ziren alemaniarrek hitzen ordenaren urraketa nola prozesatzen duten ikertu zuen Davidsonek (Davidson and Indefrey, 2009b). Partaideen MEG seinaleak jaso egin ziren hiru saio ezberdinetan, kurtsoaren hasieran, kurtsoa hasi eta bi astetara eta hiru hilabetetara. Partaideek esaldi bat irakurri eta ondorengo irudiarekin bat egiten zuten edo ez erabaki behar zuten. Lehenengo saioan, kontrol eta urraketa esaldien artean ez zen desberdintasunik topatu. Bigarren saioan, ezker goi-eremu tenporaleko aktibitatea ezberdina zen bi esaldi motetan. Hirugarren saioan, bi egoeren arteko aktibitate diferentzia aurre-eremu tenporalean kokatu zen.

Beraz, epe luzeko eta ertaineko hizkuntza ikasketan plastikotasuna topatu da bai IFGn eta bai ezker lobulu tenporalean. Hala ere, burmuinaren funtzionalidadeak epe-motzeko hizkuntza ikasketan nola aldatzen den ikertu gabe jarraitzen du. Tesi honek hutsune honi ekarpena egingo dioten bi esperimentu aurkezten ditu (3. kapitulua eta 4. kapitulua).

Plastikotasuna denbora eskala ezberdinetan ikertu daiteke ere. Aldaketa plastikoak iraunkorrak edo igarokorrak izan daitezke (Knudsen, 2004). Ariketa motoreen epe motzeko eta epe luzeko ikasketek, adibidez, aldaketa plastiko diferentek eragiten dituzte (Rossini and Melgari, 2011). Hurrengo atalek, epe luzeko eta epe motzeko ikerketa elektrofisiologikoak laburbiltzen dituzte hurrenez-hurren.

1.4 Epe luzeko hizkuntza ikasketa heldutan

Orain arteko ikerketetan, hizkuntzaren azpisistemen plastikotasuna ikertzeko neuroirudi teknikak paradigma ezberdinekin erabili izan dira. Alde batetik, zehar-sekzio ikerketek ezaugarri ezberdineko H2 hiztunen taldeak konparatzen dituzte: adibidez, H2a txikitan edo heldutan ikasitakoak, ikasteko estrategia ezberdinak erabili dituztenak, etab. (adibide bezala ikus Kotz et al., 2008; Hahne, 2001). Bestalde, luzetarako ikerketek ikastaro ofizial bat egiten duten partaide talde berdina jarraitzen dute. Partaide berdinak aztertuak dira, orokorrean, kurtso hasieran, kurtso erdian eta praktika periodo baten ondoren (adibide bezala ikus Davidson and Indefrey, 2009b; McLaughlin et al., 2010).

Duela gutxiko ikerlanek hizkuntzaren azpisistemak (adibidez, semantika, sintaktika, fonologia) sare kortikal ezberdinetan sostengatu daitezkeela azpimarratu dute (Sanders et al., 2008). Gramatika ikasketari dagokionez, gaur egun, fMRI teknika erabiliz egindako elebitasunaren inguruko ikerketei esker burmuin eremu bilduma zabala eskuragarri daukagun arren (e.g. Indefrey, 2006; Sebastian et al., 2011), elektrofisiologia bidez neurtu eta lokalizatutako aktibitateen konparazio gutxi topa daitezke. Indefrey (2006) -k laburbildutako ikerketek, morfemen prozesamenduan H1 eta H2ren arteko ezberdintasun fidagarriak erakusten dituzte, ikasketa prozesuaren hasieran ezker atzealde eremuak gehiagotan agertzen direlarik. 3, kapituluan azaltzen den esperimentuan, gramatikaren urraketak prozesatzen dituen sarea topatzeko asmoz, efektu elektrofisiologikoen iturriak lortzeko MEG teknika erabiltzen da.

Gramatika arauak erabiltzen ikasteak, hitzak eta esaldiak sortzen edo ulertzen diren bitartean gertatzen diren dependentziak identifikatzen ikastea eskatzen du askotan. Hizkuntza europar askorentzat (adibidez Gaztelera eta Alemaniera) genero, pertsona edo zenbaki konmuztadura morfosintaktikoak bezalako arau gramatikalak elementu ezberdinetako morfemek haien artean nola erlazionatzen direnaren adibide dira (Bybee, 1985). Gramatika ikasketaren inguruko ikerketek 'hiz kritiko' edo 'morfema kritiko'-ari (hau da esaldi baten erlazio gramatikal hori identifikatu daitekeen lehenengo momentuari) izandako erantzuna neurtzen dute. Portaeran izandako aldaketak burmuineko aldaketekin nola lotzen diren ulertzeko asmoarekin, hizkuntza berri baten arau ikasketa hasi aurretik eta ondoren izaten dira neurketak (Osterhout et al., 2006). Caffarra et al. (2015)-k luzetarako ikasketa ikerketetan topatutako gertakari bati lotutako sorrarazitako erantzun potentzialen (event related potential, ERP) konponente nagusiak laburbildu ditu.

Gaur egun, urraketa morfosintaktikoen erantzun bezala P600 konponente elektrikoa topatu da ikerketa ugaritan (Weber-Fox and Neville, 1996; Hahne, 2001;

Rossi et al., 2006; Frenck-Mestre et al., 2008; Kotz et al., 2008; Sabourin and Stowe, 2008; Weber and Lavric, 2008; Dowens et al., 2010; Moreno et al., 2010; Dowens et al., 2011; Foucart and Frenck-Mestre, 2012a; Pakulak and Neville, 2011; Schmidt-Kassow et al., 2011a,b; Zawiszewski et al., 2011; Foucart and Frenck-Mestre, 2012b; Xue et al., 2013; Bañón et al., 2014; Lemhöfer et al., 2014; Tanner et al., 2013). Hala ere, P600a ez da gramatika ikasketa isladatzen duen konponente bakarra.

N400 konponente elektrikoa H2 ikasleen bereizgarri bezala erabili izan da ere (Weber-Fox and Neville, 1996; Proverbio et al., 2002; Kotz et al., 2008; Weber and Lavric, 2008; Guo et al., 2009; Tanner et al., 2009; McLaughlin et al., 2010; Zawiszewski et al., 2011; Foucart and Frenck-Mestre, 2012b; Xue et al., 2013; Tanner et al., 2013). Ama hiztunek urraketa semantikoen aurrean N400 eta urraketa sintaktikoen aurrean P600 bat erakusten duten bitartean, H2 ikasleek egoera batzuetan N400 konponentea erakusten dute urraketa sintaktikoen aurrean (Isel, 2007; Proverbio et al., 2002). Emaidza hauek, H2 ikasketa prozesu hasieran ikasleek prozesu lexiko-semantikoak erailtzen dituztela arguadiatzeko erabili zen. Ondorengo ikerketa batzuek Alemaniera ikasten zuten ikasleak aztertu zituzten lehenengo maila eta hirugarren mailaren bukaeran (McLaughlin et al., 2010; Tanner et al., 2009). Hirugarren mailako ikasleek P600 erantzuna erakutsi zuten urraketa morfosintaktikoen aurrean, lehenengo mailako ikasleek aldiz, N400-P600 erantzun bifasikoa erakutsi zuten. Datu hauen analisi sakonago batek erakutsi zuen, erantzun bifasikoa partaide guztien datuen batzuek eragindako artefaktu bat zela: maila baxuagoko partaide azpimultzoak N400 erantzuna erakusten zuten bitartean, maila altuagoko ikasleek P600 erantzuna erakusten zuten. Gainera P600 aren anplitudea erabakitze ariketaren diskriminazio indizearekin positiboki korrelatzen zuen. McLaughlin et al. (2010)-ek estilo honetako ikerketa gehiago laburbildu zituen eta hurrengo proposamena egin zuen: ikasleak N400 erantzun batetik P600 erantzun batera pasatzen dira, eta ondorioz, partaide bakoitzaren erantzuna bere gramatika ikasketa etaparen menpe dago.

1.5 Epe motzeko hizkuntza ikasketa heldutan

Ikerketa elektrofisiologiako berriek ikasketa labur baten ondorioz geratutako aldaketetan jarri dute arreta, bereziki gramatika eta fonologia ikasketa laburrena (Zhang et al., 2000, 2001; Wang et al., 2003; Mueller et al., 2005, 2007, 2008; Davidson and Indefrey, 2009a,b, 2011), hauek bait dira heldutan ikastekoa razo gehien sortzen dituzten azpisistemak (Uylings, 2006). Ikerketa hauek ordu gutxi (edo minutu gutxi) batzutan ikas daitekeen hizkuntza baten gramatika arau edo kontraste

fonologikoen azpimultzo bat (hizkuntza miniatura) aukeratzen du, partaideak laborategian bertan trebatzen dira epe-motzeko hizkuntza ikasketarekin lotutako aldaketak ikertzeko. Hizkuntza miniaturen abantaila bat ikasketa prozesuaren eta lortutako gaitasunen gainean kontrol handiagoa ahalbidetzen dutela da. Gainera, ikasi beharreko ezaugarrien kontrol zorrotzago bat ahalbidetzen dute, hizkuntzaren ezaugarri oinarrikoak errespetatzen direlarik.

Prozesamendu fonologikoari dagokionez, Zhang et al. (2000, 2001)-ek partaide japoniarrak, japonieran existitzen ez den kontraste batean (r-l) trebatu zituzten. Partaideak artikulazio keinuen laguntzaz 12 ordu inguruz izan ziren trebatuak r-l kontrastean eta MEG seinaleak trebakuntza aurretik eta ondoren grabatu ziren. Grabaketa hauen bitartean Bateraegin Negatibotasun magnetikoa (magnetic Mismatch Negativity, mMMN) izena duen konponente magnetikoa neurtu zen burmuinak bi soinuak ezberdintzeko zuen gaitasunaren erakusgarri bezala. Portaeran, trebakuntzaren ondoren partaideek %20 hobetu zuten soinuak baztertzeko gariaian. Bestalde mMMN konponentea kortex auditiboan kokatu zen eta bi saioen artean mMMN konponentean topatutako aldaketak portaerako aldaketekin korrelatu zuen.

Beste ikerketa batek ama hizkuntza Ingelera estatubatuarra zuten hizlariak Txinatar Mandarinoko tonuetan trebatu zituzten (Wang et al., 2003). Trebakuntza aurretik eta bi asteko trebakuntza ondoren, partaideen MRI datuak bildu egin ziren hauek tonu bereizketa ariketa bat egiten zuten bitartean. Portaeran topatutako hobekuntzak ezker-atze lobulu tenporalean eta IFG burmuin eremutako aktibitate igoerarekin lotu egin ziren.

Gramatikari dagokionez, EEG teknika erabiliz urraketei-lotutako konponeentetan epe-motzeko aldaketak ikusi izan dira. Testu materialak erabiliz Davidson and Indefrey (2009a)-k P600 bezalako ERP konponenteak eta gramatika ikasketa prozesua heldutan nola erlazionatzen diren ikertu zuen. Trebakuntza bitartean eta ondoren Holandesa ikasten zuten alemaniarrek P600 konponentearen antzeko erantzun bat izan zuten (ama hizkuntza Alemaniera zutenaren antzeko erantzuna), baina soilik, gramatika urraketa mota batzuetan. Antzeko ikerketa batean (Davidson and Indefrey, 2011), P600 konponentea topatu zuten bai genero eta bai deklasio urraketeetan, berriz ere testu materialak erabiliz. Bestalde, MEG teknika erabili zuten Holandesa ikasten zuten alemaniarrengan sintagma ordenaren urraketa seinaleak bildu eta hauen adierazle anatomikoak ikertzeko (Davidson and Indefrey, 2009b). Ikerketa honetan ere testu materialak erabili ziren entzutezko materialak erabili ordez, eta trebakuntza laborategitik kanpo eman zen, luzetarako diseinu bat erabili zen ikasgela batean trebatzen ari ziren ikasleak jarraituz. Beraz, ez dago argi ea

ikerketa honetan topatutako bumruin eremuak laborategian burututako trebakuntza zehatzago batean agertuko diren edo ez.

Beste epe-motzeko ikasketa ikerketa batzuek sensore-mailan material auditiboek eragindako urraketa efektuak aztertu dituzte. Testu bidez aurkeztutako materialen aldera, material auditiboak segmentatu egin behar dira ulermenaren bitartean eta gramatikaren jabetza erritmoa modulatu dezake alde batetik ikasleek elementu lexiko bakoitza identifikatu behar dutelako eta bestetik jakina da fonologia ikasleentzat arazo bat dela. Muellerrek erakutsi zuen material auditiboak erabilia ere, ama hizkuntzan gramatika urraketa ematen diren ERP patroien efektu antzekoak topatu daitezkeela ikasleengan trebakuntza ondoren, nahiz eta ezberdintasun batzuk egon ikasle eta ama hiztunen artean (Mueller et al., 2005). Ikerketa honetan ama hizkuntza Alemaniarra zuten partaideak Japonieraren hizkuntza miniaturizatu (lexiko eta gramatika arau murriztuak) batean izan ziren trebatuak eta hiru gramatika urraketa ezberdinetan izan ziren aztertuak (hitz kategoria, kasua eta klasifikatzailea). Partaideek trebakuntza aurreko test bat, ulermenean eta mintzamenean oinarritutako trebakuntza eta trebakuntza ondorengo test bat burutu zituzten. Partaideek lau eta hamar ordu arteko trebakuntza izan behar zuten urraketa guztietan gaitasun altua erakusteko; eta horietako bietan (hitz kategoria eta kalsifikatzailean) ama-hiztunen maila erakutsi zutelarik. Bi urraketa mota hauetan, trebakuntza ondoren baina ez aurretik, ama hiztunen antzeko P600 efektua erakutsi zuten partaideek. Hala ere, ma-hiztunek erakutsitako N400a ez zuten partaideek erakutsi. Hurrengo ikerketa batean (Mueller et al., 2007), ama-hiztunen eta partaideek erakutsitako P600 aren artean ez zen ezberdintasunik topatu, baina, partaideek aurreko negatibotasuna soilik esaldi kanonikoetan erakutsi zuten. Azkenik, ondorengo ikerketa batean (Mueller et al., 2008), pseudohitzez osatutako materiala erabiliz, trebatutako partaideek ama -hiztunen N400-P600 patroia erakutsi zuten. Emaitza hauek erabiliz karga semantikoa eransteak urraketa sintaktikoak prozesatzeko baliabideak libratzen dituela argudiatu zuten.

Ikerketa gutxik aztertu dute nola sortzen den mintzamena epe-motzeko ikasketa bitartean. Hutsune garrantzitsua da hau, ikasleek gramatika ulermena eta mintzamena erabiliz ikasten bait dute (Mueller et al., 2005). MEG teknika erabiliz, partaide finlandiarrak hizkuntza artifizial batean trebatuak izan ziren (Hultén et al., 2014). Trebakuntza lau egunez egin zen eta bertan partaideek marrazki bat ikusi, eta honekin bat egiten zuen esaldi bat entzun eta irakurtzen zuten eta azkenik esaldia errepikatzen zuten. Ariketa partaideek inflekzio konmutadura egokia aukera zezaten prestatua zegoen. Esperimentua ama hizkuntzan (H1) eta hizkuntza artifizialean (H2) burutu zuten. Esperimentuko emaitzek erakutsi zuten bi hizkuntzen mintzamenaren sare neuronalak elkarbanatzen dituztela. Hala ere, H2an ezker

lobulu parietalean eta zirkunboluzio angularrena topatutako anplitude igoera ikusita Huletenk proposatu zuen H2-n sortutako mintzamenak esfortzu kognitibo handiagoa eskatzen zuela (ikus ere Hanulová et al., 2011).

Laburbilduz, mota honetako epe-motzeko ikasketa diseinuek burmuin aldaketak ikasketa gertatzen ari den bitartean neurtzea ahalbidetzen digute eta, ondorioz, hizkuntza ikasketaren perspektiba berri bat eskaintzen dute. Atal honetan aipatutako ikerketa guztiek epe-motzeko plastikotasuna gertatzen dela eta teknika ez inbasiboen bitartez neurtu dezakegula ondorioztatzen dute. Hala ere, aipatutako ikerketa gehienek EEG teknika erabili dute eta ez dute ikasketaren adierazle anatomikorik aurkezten. Adierazle anatomikoak garrantzitsuak dira, ariketetan gertatzen diren adierazle hauen modulazioek jasotzen bait dute ikasketa prozesuak eragindako epe-motzeko kortexaren plastikotasuna. Era honetako epe-motzeko plastikotasuna beste domeinu batzuetan jasoak izan dira, adibidez ikasketa motoretan (Rossini and Melgari, 2011), baina sarreran azaldu bezala hizkuntza ikasketan epe-motzeko adierazle anatomikoak falta dira. Tesi honek epe-motzeko hiztegi eta gramatika ikasketaren adierazle anatomikoak aurkezten ditu, eta lehenengo ikerketa non trebakuntza MEG grabaketa bitartean burutu egin den.

1.6 Laburpena

Kapitulu honek burmuin plastikotasuna denbora eta espazio eskala ezberdinetan nola ulertu daitekeen azaldu du. Hizkuntza ikasketak sortutako burmuin aldaketak ulertzeko, burmuin-osoko aldaketak denbora labur batean neurtzen dituen teknika bat behar dela argudiatu da. Horregatik, tesi honek MEG teknika erabiltzen du epe-motzeko hizkuntza ikastearekin lotutako plastikotasuna ikertzeko. MEG teknikaren datu bilketa eta analisiaren oinarriak 2. kapituluan azaltzen dira.

2. Kapitulu

Burmuin aktibitatea neurtzen Magnetoentzefalografiarekin

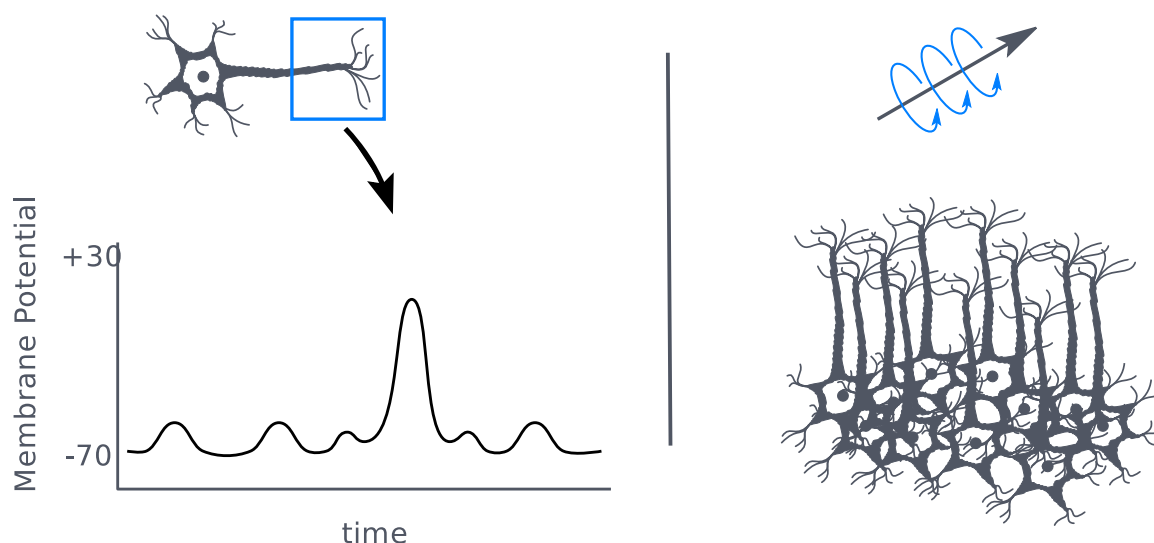
Kapitulu honen helburua tesi honetako esperimuetan neurtutako aktibitate mota azaltzea da. Honetaz gain, datu bilketarako behar diren MEG teknikaren oinarriak eta datuen analisirako metodologia azaltzen dira.

2.1 MEGak jasotzen duen burmuin aktibitatea

EEG eta MEGekin ez inbasiboki neurtutako aktibitate elektriko eta magnetikoek joera dute neurona mota naztuetako aktibitate mota konkretu batzuk jasotzeko.

Neuronak elkarrekin komunikatzeko, sinapsietan neurotransmisoreak askatzen dituzte (Ramón y Cajal, 1904). Seinalea bidaltzen duen neuronaren atala terminal pre-sinaptikoa deitzen da eta jasotzen duena terminal post-sinaptikoa. Terminal post-sinaptikoetako mintz-potentzial aldaketak potentzia post-sinaptikoak deitzen dira. Fisikoki egoki kokatuta dauden neurona talde handi bat sinkronizatzean (Lorente de No, 1947), hauen potentzial post-sinaptioken fluktuazioek EEG eta MEG teknikek neurtu dezaketen korrante bat sortzen dute (ikus 2.1 irudia). Fluktuazio hauei, patroirritmiko edo errepikakor bat jarraitzen dutenean, oszilazio neuronalak deitzen zaie. Burmuin fisiologian oszilazio hauek bandatan banatzen dira fluktuazio frekuentzia oinarrituta: delta banda (1-4 Hz), theta banda (4-8 Hz), alpha banda (8-13 Hz), beta banda (13-30 Hz) eta gamma banda (>30 Hz).

Estimuluek eraginda oszilazio hauek antolatu, amplifikatu edota parekatzen dira, bi motatako erantzunak sortuz: erritmo 'sorrarazia' (estimuluari gogorki lotuta) edo erritmo 'induzitua' (estimuluari ahulki lotuta). Sorrazitako erantzunak aztertzeko, normalean, denborari-lotutako batezbestekoa kalkulatu da eta honen emaitza



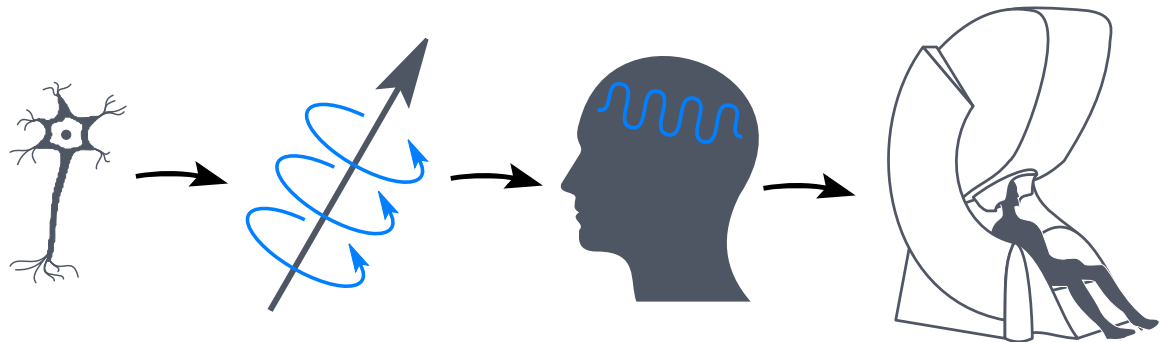
2.1. irudia: Seinale postsinaptikoak. Ezkerreko panelak neurona solte baten mintz potentzial post-sinaptikoa irudikatzen du (grisa). Eskubiko panelak neurona talde baten potentzial post-sinaptikoen sortutako korrante neurgarria (grisa) eta honen eremu magnetikoa (urdina) irudikatzen ditu.

sorrarazitako erantzun eremua (evoked response field, ERF) edo sorrarazitako erantzun potentziala (evoked response potential, ERP) deitzen da (MEG edo EEG seinaleen kausa hurrenez-hurren). Bestalde, denbora-frekuentzia analisia erabili ohi da induzitutako erantzunak aztertzeko.

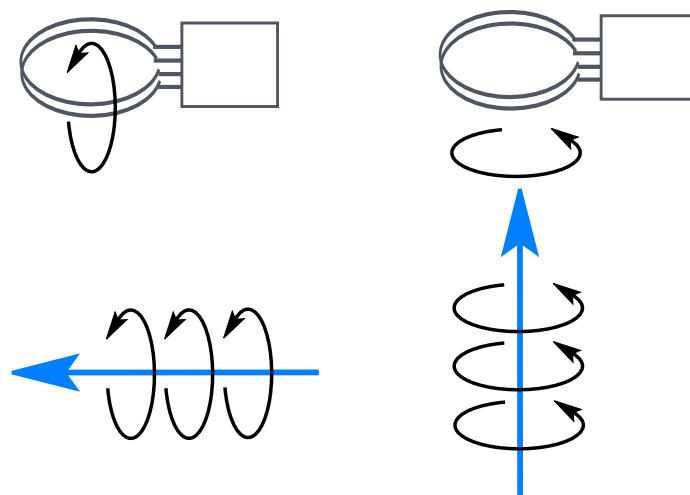
2.2 MEGaren oinarriak

Edozein korrante elektrikok bezala, korrante post-sinaptikoak berari proportzionala den eremu magnetikoa sortzen du bere inguruan. Eremu hau burmuinaren mintz ezberdinetatik (materia grisa, txuria, likido zerebroespinala), gazezur eta larruazaletik igarotzen da eta buru kanpoaldean neurtu daiteke MEG sensoreak erabiliz (ikus 2.2 irudia).

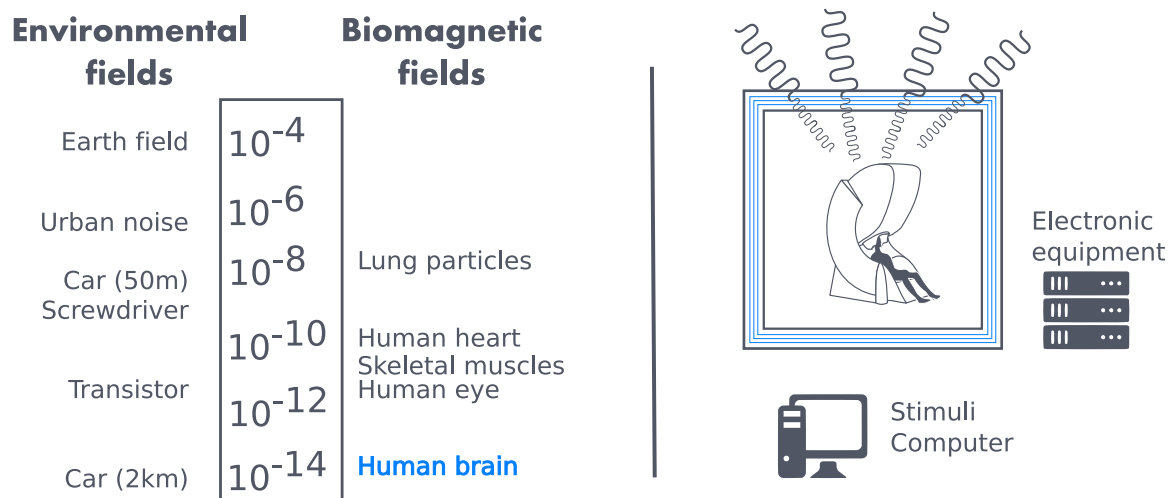
MEG sensoreak material supereroalez eginiko uztaiak dira. Eremu magnetiko batek uztaiak gurutzatzean, eremuari proportzionala den korrante bat sortzen eta jasotzen da uztaian. Desabantaila nabari bat du sensore mota honek: neuronen norabidean arabera, sortutako eremu magnetikoa ezin da neurtu. Larruazalari erradialak diren korranteek sortutako eremu magnetikoek ez dituzte sensoreak zeharkatzen, bestalde, larruazalari tangenzialak diren korranteek sortutako eremu magnetikoak bai. Ondorioz, soilik korrante tangenzialek (eta ez erradialek) sortutako eremu magnetikoak neurtu daitezke MEG teknikarekin (ikus 2.3 irudia; Hari, 1991).



2.2. irudia: Magnetoentzefalografiak jasotako seinalearen eskema. Korrante sorreratik (ezkerra) seinale neurketararte (eskuina).



2.3. irudia: Korrante elektriko ezberdinak eta beraien eremu magnetikoa. Ezkerreko panelak korrante tangenziala eta honek eragindako eremu magnetikoak sensorea nola gurutzatzen duen irudikatzen ditu. Eskuineko panelak korrante erradiala eta honek eragindako eremu magnetikoak sensorea ez duela gurutzatzen irudikatzen ditu.



2.4. irudia: MEG seinalea eta zarata. Ezkerreko panelak MEG seinalea eta bestelako iturri magnetikoak (zarata) alderatzen ditu. Eskuineko panelak zarata hau indargabetzeko erabiltzen den pantailatze gelaren eskema irudikatzen du.

Neurketak burutu ahal izateko, MEG ekipamenduaren pantailatze egokia beharrezkoa da. Burmuinaren sortutako eremu magnetikoa oso txikia da ingurunean dauden beste eremu magnetikoekin alderatzen denean (ikus 2.4 irudia). MEG ekipamendua pantailatze egokirik ez balu, sensoreek ingurumeneko eremu magnetikoak neurtuko lituzkete eta interesdun seinalea (burmuineko eremu magnetikoa) zaratatik antzemanekin bihurtuko litzateke. Hau ekiditeko, ingurumeneko eremu magnetikoak blokeatzen dituen gela-pantailatu batean kokatzen da MEG ekipamendua, neurketa gunean kanpo eremuen eragina ahalik eta gehien txikitzeko. Honetaz gain, saio esperimental guztien aurretik partaide eta ikertzaileek neurketa gunean bestelako zarata iturririk sartzen ez dutela ziurtatzen da. Zarata indargabetzeaz gain, pantailatze gelak soinua indargabetzen du, inguru isila sortaraziz. Hau bereziki garrantzitsua da material auditiboak erabiltzen dituzten ikerketentzat.

Datu analisien helburua sensoreetan neurtutako eremu magnetikoa sortu duen aktibitate elektrikoaren kokapen eta ezaugarriak berreraikitzea da. Hau da, ariketa bat egiteko erabilitako burmuin eremuak aurkitu eta ariketa manipulatzeko eremu hauetan neurtutako aktibitatea nola moldatzen den aztertzea.

2.3 MEG datuen analisisa

Atal honek tesi honetako esperimentuetan jasotako datuak analizatzeko erabilitako metodologia azaltzen du. Analisi metodo bakoitzaren azalpenarekin

batera 'Nola azaltzen da hau Metodoak atalean?' deitzen den azpiatal bat agertzen da, atal metodologikoetan analisisen deskribapen adibide bat aurkezten duelarik. Beraz, azpiatal hauek kapitulu esperimentalen metodo atalak ulertzeko gida bezala hartu behar dira eta ez tesi osoko metodoen deskribapen amankomun bat bezala. Esperimentu bakoitzak bere berezko analisiak eta hauen parametroak deskribatzen dituen metodo atala du.

Tesi honetako datuak bi MEG ekipamendu ezberdinetan bildu ziren: Elekta Neuromag (Elekta AB, Stockholm, Sweden) eta CTF System (MISL, Coquitlam, Canada). Neuromag ekipamendua 102 kokalekutan banatutako 306 sensorez osatua dago. Kokaleku bakoitzean magnetometro bat eta bi gradiometro planar ortogonal aurkitzen dira. CTF ekipamendua ordea, 275 gradiometro axialez osatua dago. Gradiometro axialak eta magnetometroak burmuinean sakon sortzen diren seinale magnetikoak neurtzeko aproposak dira, gramdiometro planarrak, aldiz, magnitude txikiko seinale magnetikoak neurtzeko aproposak dira. MEG ekipamendu bakoitzak zarata murrizteko berezko software bat dakar.

Datuen preprozesamendua

Datuen preprozesamenduan ematen diren pausuak, interesa duten datuak interesa ez duten datuetatik (zarata, ezagutzen diren artefaktuaK) banantzeko helburua dute.

- Zarata indargabetzea. Datuak pantailatze gela barruan biltzen diren arren, kontuan hartzeko moduko zarata iturriekin kutsatuta jasotzen dira datu hauek. Horregatik, MEG ekipamendua berezko zarata indargabetze softwarearekin batera erabiltzen da.

Elekta Neuromag ekipamenduaren software Maxfilter deitzen da eta honen datu garbiketa Espazio Seinale Banaketa (Signal Space Separation SSS) deitzen den metodo batean oinarritzen da (Taulu et al., 2005). Metodo honek seinale elektromagnetikoen eta hauen oinarritzko frekuentzien ezaugarriak erabiliz MEG datuak hiru konponentetan banatzen ditu: Ekipamenduko sensore array barruan sortutako seinaleak (b_{in}), sensore array kanpoko zaratak (b_{out}) eta sensore arraytik gertu sortutako zarata (b_s). Zaratarekin lotutako konponentak baztertuak dira. Tesi honetan metodo honen espantsio tenporala erabiltzen da (tSSS), non konponente bazterketa denbora leiho irristakor bat erabiliz egiten den (Taulu and Simola, 2006). Honek zarata murrizteko informazio

espaziala eta tenporala erabiltzea ahalbidetzen du. Algoritmoak b_{in} eta b_s konponenteen arteko korrelazio altuak bilatzen ditu, artefaktuen adierazle bait dira. Hau aurrera eramateko, softwarrak parametro batzuk eskatzen ditu: denbora leihoaren luzera, korrelazio ataria, buruaren jatorrizko kokalekua eta sensore zaratatsuen zerrenda. Behin datuak iragazita, buruaren kokalekua kokaleku lehenetsira (0,0,40) transformatzen da, partaide guztien kokaleku amankomuna izan dezaten eta datuen sensore-topopgrafiak konparagarriak izateko.

CTF ekipamenduak berak 3. milako gradiometro sistema bat dakar. Gradiometro hauek eta preprozesamendu sistemak, gradiometro axialetan neurtutako datuak garbitzen dituzte erabiltzaileak parametririk zehazteko beharrik gabe.

Bi ekipamenduentzat, zarata indargabetze algoritmoarekin batera linea elektrikoaren frekuentzia (50 Hz) baztertzen da eta datuen lagintze-abiadura jaisten da (downsample) lan konputazionala murrizteko. Tesi honetan lagintze-abiadura jaitsiera eta linea frekuentziaren iragazketa bi pausu banandutan egiten da.

Nola azaltzen da hau Metodoak atalean? (Elektro Neuromag ekipamenduaren adibidea)

MaxFilter 2.2 erabilia MEG datuak Espazio Seinale Banaketa tenporalarekin (temporal Signal Space Separation tSSS) iragazki ziren X segunduko denbora leihoa eta Xko korrelazio minimoa erabiliz. Partaide bakoitzaren buruaren jatorria eta sensore zaratatsuen zerrenda eskuz markatu ziren, datuen lagintze-abiadura X Hz-ra jaitsi zen eta linea elektrikoaren frekuentzia (50 Hz) eta honen harmonikoak iragazki ziren. MRC Cognition and Brain Science Unitek duen MEG laborategiaren gomendioak jarraituz, lagintze-abiadura jaitea eta iragazketa bi pausu ezberdinetan egin zen, softwareak duen akats baten ondorioz datuen kutsadura ekiditzeko (http://imaging.mrc-cbu.cam.ac.uk/meg/Maxfilter_V2.2). Partaide bakoitzaren buruaren kokalekua, kokaleku lehenetsira transformatu zen, partaide eta blokeen artean buru kokaleku amankomuna zegoela ziurtatzeko. Batazbetse, lehen egunean buruen posizioak Xmm (std=X) aldatu ziren eta bigarren egunean X mm (std=X).

- Segmentazioa. Hurrengo pausua datuak intereseko zatitan moztea da: segmentuak sortzea. Segmentuaren tamaina esperimenduaren diseinuaren

araberakoa da. Ohikoa da ere segmentu hauek erreferentziako base bezala ezagutzen den intereseko leihoen aurreko datuak ere hartzea. Erreferentziako base hau estimulu aurreko eta ondorengo (periodo aktiboa) aktibitatea konparatzeko erabiltzen da, burmuinaren dinamikak aztertzeko.

- Artefaktu bazterketa. Pausu honen helburua ondorengo analisisien aurretik zarata diren segmentuak topatu eta baztertzea da. Pausu hau eskuz (miaketa bisuala, visual screening) edo automatikoki egin daiteke. Automatikoki egiten denean, soilik artefaktu baztertze pausurako, datuak estandarizatuak dira (adibidez, seinalea prozesu Gaussiano bat bada z -transformazio bitartez estandarizatzen dira) eta atari batean oinarrituta artefaktuak kontsideratzen diren segmentuak baztertzen dira. Bazterketa egin ondoren, datuak jatorrizko unitatetan mantentzen dira ondorengo analisisietarako.
- Iragazketa. Aldez aurretik intereseko aktibitatea frekuentzia jakin batzuetan aurkitzen dela dakigunean, soilik frekuentzia horiek mantentzeko datuak iragazki daitezke. Segmentuen iskinetan iragazkiak nahi ez diren efektuak sortu ditzake eta hauek ekiditzeko zero betegarriak (zero padding) erabiltzea gomendagarria da. Tesi honek hiru iragazki mota erabiltzen ditu eta iragazki bakoitzean ebaki-egoera bat edo bi aukeratu behar dira. Behe-paseko iragazkia ebaki-egoera azpitik dauden frekuentziak mantentzen ditu, goi-paseko iragazkiak ebaki-egoeratik gorakoak eta banda-paseko iragazkiak emandako bi ebaki-egoeren (behe eta goi frekuentziak) artean dauden frekuentziak.
- Korrante zuzeneko offset tentsio eta joera zuzenketak. Pausu ohiko bat korrante zuzeneko offseta (DC offset) eta seinalearen joera eliminatzea da. Korrante zuzeneko offseta seinalearen batezbesteko balioa da. Egoera ezberdineko segmentuek korrante zuzeneko offset ezberdina badute emaitzak oker ulertu daitezke, ez dauden seinale ezberdintasunak aldarrikatuz edota daudenak ez aldarrikatuz. Hau ekiditeko seinalearen batezbesteko balioa seinaletik kendu egiten da. Pausu hau ere demeaning bezala ezagutzen da. Batezbesteko balioa soilik erreferentzia basea erabiliz kalkulatu denean, erreferentzia zuzenketa bezala ezagutzen da pausu hau. Bestalde, zarata magnetiko handiek seinalean sortzen dituzten joera linearrak indargabetu daitezke joeraren estimazio linearra seinaletik kenduz (detrending).

Pausu hauek ondoren egingo diren analisisien baitan burutzen dira. Denbora-Frekuentzia analisi batean biak baztertzea egokia da, bai korrante zuzeneko offseta eta bai joera linearraren potentziek denbora-frekuentzia

puntuetara ihes egiten bait dute (Fieldtrip Online Users Tutorial, 2013). Sorrazitako eremu erantzunen (ERF) analisiaren kasuan, erabakia ez da hain argia. Erreferentzia zuzenketa seinale-zarata-ratioa hobetzeko erabili ohi da. Segmentu bukaerara irauten duten konponente berantiarak badaude, joera linearra kentzeak konponente horiek ere kenduko lituzkete (egiazkoa eta sorrazitakoak direnak) edo existitzen ez diren konponente berantiarak sortuko lituzke. Bestalde, artefaktuek jitoa sortzen badute seinalean, joera linearra kentzea egokia da (Acunzo et al., 2012).

- Begi-mugimendu eta bihotz-taupaden seinale zuzenketa. Begi-mugimenduek eta bihotz-taupadek datuak kutsatzen dituzten seinale elektriko eta magnetiko handiak sortzen dituzte. Ohiko bi modu daude seinale hauek baztertzeko. Lehenengoa, bihotz-taupadak edo begi-mugimendu efektu argiak dituzten segmentuak bisualki identifikatu eta baztertu daitezke. Bigarrena, segmentuetatik begi-mugimenduen eta bihotz-taupaden konponenteak baztertu daitezke, segmentu osoa baztertu ordez. Azken aukera hau hobea da, segmentu gehiegi baztertzeko ondorengo analisisetarako seinale-zarata-ratioa (SNR) jaitsiko luke eta. Elektrokardiograma (EKG) eta elektrokulograma (VEOG eta HEOG) eskuragarri badaude, begi-mugimenduen eta bihotz-taupaden efektuen antzematea automatikoki egin daiteke. Horretarako, datuak konponente bakoitza bestearen independienteak diren espazio batetara proiektatzen dira. Prozesu honek Konponente Independienteen Analisia (Independent Component Analysis, ICA; Vigário et al., 1998) du izena. Ondoren, EKG edo EOG seinaleekin korrelazio altuenak dituzten konponente independienteak baztertu egiten dira. Azkenik, baliozko konponenteak jatorrizko espaziora (kasu honetan sensore espaziora) proiektatzen dira berriz ere.

Nola azaltzen da hau Metodoak atalean?

Datuak Fieldtrip tresna erabiliz prozesatu ziren (version 20141202, Oostenveld et al., 2011). Lehenik, datuak segmentatuak izan ziren. Segmentuaren hasiera entsaioaren hasierakin lotu zen. Datuak X segunduko luzerako segmentutan banatu ziren, segundu bat entsaio hasiera baino lehen eta X segundu hasieraren ostean. Ondoren, datuak ikuskatu ziren artefaktuak bilatzeko: z -balioa X tik gora zuten segmentuak automatikoki baztertuak izan ziren. Segmentu bakoitza X segundutara iritsi arte zero-betegarriekin luzatu zen. X Hz-tan ezarritako behe-paseko FIR iragazki bat (zero-faseko pasada bakarra) erabili zen, eta X ms-ko ($-X - X$ ms) erreferentzia zuzenketa egin zen. Datuak

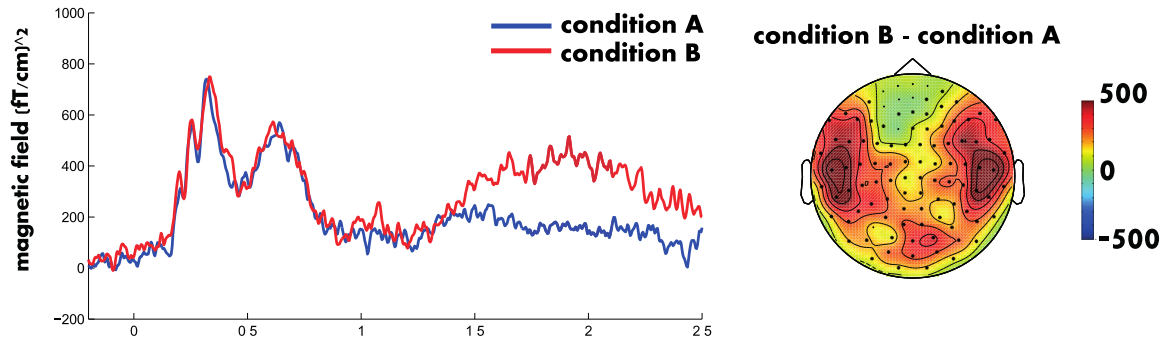
Konponente Independienteen Analisia (ICA) algoritmoa erabiliz deskonposatu ziren. Konponente kopurua, gradiometro kopurua izan zen (X) eta analisi honen aurretik ez zen dimentsio murrizketa algoritmorik erabili. fastICA algoritmoa erabili zen konbinatu gabeko gradiometritan (X sensore). Ondoren, ICA konponente bakoitza HEOG; VEOG eta EKG seinaleekin korrelatu zen. Hiru desbideratze tipikotik gorako korrelazioa erakutsi zuten konponenteak baztertu egin ziren eta konponenteak jatorrizko sensore espaziora transformatu ziren.

Denborari-lotutako analisia

Segmentu batean dagoen estimulu solte baten erantzuna oso zaratatsua eta zaila da deskribatzeko. Praktikan, estimulu komun baten erantzunak dituzten segmentuen (egoera bereko segmentuak) batezbesteko kalkulatzen da, seinale-zarata-ratioa hobetuz. Honetarako, intereseko efektua estimulari denboran eta fasean lotuta dagoela asumitzen da (sorrarazitako erantzun bat dela). Ondorioz, batezbestekoa kalkulatzean zarata indargabetzen da (zarata estimuluarekiko independentea dela asumitzen da), denboran eta fasean lotutako efektua argituz. Analisi mota hau MEG datuetan burutzen denean, batezbesteko seinalea sorrarazitako erantzun eremua (Event Related Field, ERF) du izena eta EEG datuetan burutzen denean sorrarazitako erantzun potentziala (Event Related Potential, ERP). Orokorrean, metodologia atalak segmentuak entseguaren zein denbora-puntura dauden lotuta adierazi beharko luke. Gainera, zein segmenturen (egoera honetako guztiak, erantzun zuzena zutenak soilik, bi egoera hauetako segmentuak etab.) eta ze sensoreen batezbestekoa egin den adierazi behar du. Ondoren, aukerazko pausu bat gradiometroak konbinatzea da, Pitagorasen araua erabiliz gradiometro horizontal eta bertikalak konbinatuz. Konbinatutako gradiometro planarrak irudikatzen direnean, sorrarazitako eremuak iturriaren gainean gailur bat erakusten du.

Normalean egoera ezberdinetako batezbestekoak grafika berdinean irudikatzen dira, non X ardatzak denbora adierazten du eta Y ardatzak eremu magnetikoaren magnitudea (ikus 2.5 irudia). Magnitudea azalerako eremu magnetiko karratua denean ($(\text{fT}/\text{cm})^2$) grafikoak konbinatutako gradiometroak irudikatzen ditu. Magnitudea gradiente magnetikoa denean (fT/cm) grafikoak konbinatu gabeko gradiometroak irudikatzen ditu. Normalean, ERF grafika bat topoplot batekin dator. Topoplota denbora lehio batean ERFen distribuzio topografikoa irudikatzen duen grafiko bat da. Topoplot batek, bi ERFen arteko ezberdintasunaren distribuzio topografikoa irudikatu dezake ere (ikus 2.5 irudia). Mapa topografikoek efektuen kokalekua modu orokor batean (ezker hemisferioa, eskuin hemisferioa, aurrekaldea, atzekaldea) adierazten dituzte. Are gehiago, mapa topografikoak iturrien analisisien

Event Related Analysis (ERF)



2.5. irudia: Denborari-lotutako analisi baten emaitza baten adibidea.

erantzunak balioztatzeko erabili daitezke, iturri analisisien emaitzak eta mapa topografikoak koherenteak izan behar dira eta (mapa topografikoak efektua aurreko eskuin sensoreetan kokatzen badu, susmagarria da iturri analisiak efektua ezker-atzekaldean kokatzea).

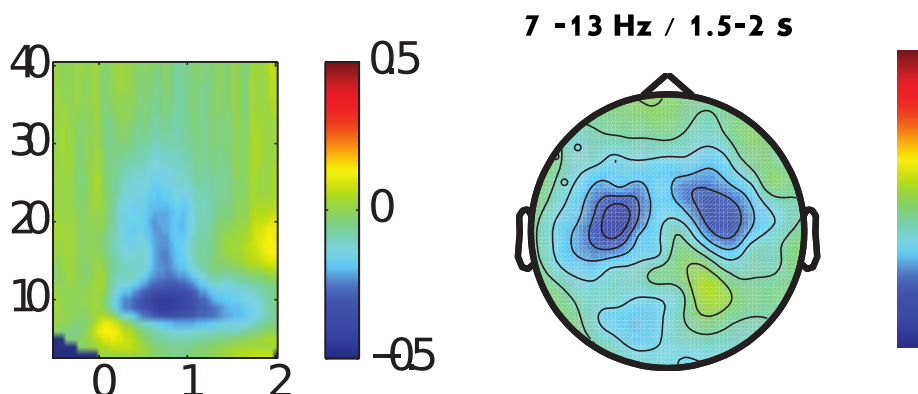
Nola azaltzen da hau Metodoak atalean?

Konbinatu gabeko sensoreetan entsaioen batezbestekoa kalkulatu zen egoera bakoitzeko (urraketa/kontrola). Soilik erantzun zuzenekin lotutako entsaioak erabili ziren gertaera bati lotutako eremuen (ERF) kontrasteetan. Batezbestekoak kalkulatu ondoren, gradiometro planarrak konbinatu egin ziren.

Denbora-Frekuentzia analisisa

Gertaera bati lotutako eremuak aztertzeko denborari-lotutako analisisa egokia den arren, burmuin erantzun guztiak ez daude estimulari denboran eta fasean hertsiki (estuki) lotuak (aktibitate induzitua). Oszilazio induzituak burmuinaren berezko aktibitatean estimulu batek eragindako modulazioa da. Erantzun induzituaren batezbestekoa egitean, hauek kantzlatu daitezke entsaio bakoitzak fase ezberdina izan dezakeelako. Oszilazio mota hauek aztertzeko denbora-frekuentzia analisisa erabili ohi da, seinalearen epe-motzeko potentzia-espektru aldaketak aztertzen dituelarik. Planteamendu matematiko ugari daude analisi hau burutzeko. Tesi honetan erabilitakoa Hanning leihoan oinarritzen da. Leiho irristakor baten bitartez datuak Hanning leiho batekin biderkatzen dira, ihes espektrala murriztuz eta frekuentzia leuntzea kontrolpean izateko. Denbora leihoaren luzera aldatu egiten da frekuentziaren baitan (leihoaren luzera frekuentzia baten ziklo kopuru bat da), denbora bereizmena hobetzeko. Geroz eta frekuentzia altuagoa, orduan eta leiho txikiagoa eta denbora-bereizmen hobea lortzen dira. Hala ere, honek frekuentzia

Time Frequency Analysis



2.6. irudia: Example of a time-frequency analysis result report.

leuntze handiagoa dakar eta horregatik metodoetan frekuentzia leuntzea adierazi behar da. Denbora leihoaren luzera batean dauden frekuentzia ziklo kopurua eta denbora leihoak aurreratzeko erabilitako pausuak ere adierazi behar dira. Fasean ez dauden erantzunen arteko kantzelazioak ekiditeko, denbora-frekuentzia entsaio bakoitzean kalkulatu da eta ondoren guztien batezbestekoa kalkulatu da.

Denbora-frekuentzia analisisen emaitzak kolore mapetan irudikatzen dira, non X ardatzak denbora adierazten du, Y ardatzak frekuentzia eta kolore eskalak erreferentziarekiko egon den potentzia aldaketa irudikatzen du (ikus 2.6 irudia). Kolore mapa hauek topoplot batekin etor daitezke, frekuentzia banda eta denbora leiho jakin bateko potentziaren topografia irudikatzen duelarik.

Nola azaltzen da hau Metodoak atalean?

Potentzia balioak frekuentzia-menpeko luzera duen Hanning leiho simple bat erabilia egin zen. Denbora leiho bakoiztean X ziklo zeuden, X s-ko pausuekin. Analisia segmentu guztian burutu zen (-X eta X s artean) X eta X Hz artean hertzio bateko pausuekin. Honek X Hz-tara X Hz-ko frekuentzia leuntzea dakar. Denbora-frekuentzia puntu bakoitzeko potentzia balioak erreferentzia basearekiko (-X,X normalizatu ziren. Ondoren, gradiometroak konbinatu eta konbinatutako gradiometroetan burutu ziren analisi estatistikoak.

Iturri analisisia

MEGren abantaila nagusia burmuineko iturri posibleen kokalekua ahalbidetzen duela da. Kokaleku horiek lortzeko joanerako modeloa (leadfield) definitu behar da. Joanerako modeloak burmuineko kokaleku bakoitzeko aktibitatea sensoreetan nola isladatuko zen azaltzen du. Joanerako modeloa kalkulatzeko burmuina geruza ezberdinetan zatitzen da (larruazala, buru-hezurra, materia grisa...) eta geruza bakoitzari eroaltasun balio bat ematen zaio. Literaturan joanerako modeloak definitzeko modu anitzak topa daitezke. Tesi honetan geruza bakarra (single shell) deituriko hurbilketa erabili da (Nolte, 2003). Honetaz gain, lauki-sare (spatial grid) baten barruan kokaleku multzo bat espezifikatu behar da. Joanerako modeloan oinarrituta alderantzizko modelo/erantzuna kalkulatu da, neurtutako seinaleak sortu lezaketen burmuin iturriak estimatuz. Algoritmo ezberdinak daude alderantzizko modeloak kalkulatzeko, ondorengo paragrafoetan tesin honetan erabilitakoak azaltzen dira.

Minimum Norm Estimation (MNE, Hämäläinen and Ilmoniemi, 1994) burmuineko korrante banatuak kalkulatzeko estimazioaren teoria erabiltzen duen iturri berreraikitze metodo bat da. Aurreupoastu bakarra iturri korranteak eremu batera mugatuta daudela da, burmuinera hain zuzen ere. Estimazioa iturri-korrante espazioan dagoen bektore motzena da, hau da, orokorrean energia minimoa erabiliz neurtutako seinaleak azaldu daitezkeen iturri banaketa. Metodo guztien artean, MNE sorrarazitako erantzunak analizatzeko eta burmuinean zabaldutako aktibitatea denboran zehar jarraitzeko erabili ohi da. Tesi honetan erabilitako MNE bertsioa fieldtripen eskaintakoa da (Dale et al., 2000).

Nola azaltzen da hau Metodoak atalean?

*Minimum Norm Estimate (MNE) (Dale et al., 2000) metodoa erabili zen. MRI egitura irudiak larruazal, garezur, burmuin eta CSF mintzetan segmentatu zen, eta geruza bakarra modeloa erabiliz burmuinaren bolumenari eroaltasun balio bat eman zitzaion. Bolumenaren eroaltasun modeloa eta geruza kanoniko kortikalean oinarritutako X-puntuko sarea (Fieldtripen eskuragarri) erabiliz leadfilak eraiki ziren. Alderantzizko emaitza kalkulatu aurretik, leadfilak txurituak izan ziren. Iturrien kobariantza matrizea eskalatua izaten da ondorengo ekuazioa bete dezan: $\text{trace}(A^*R*Aff)/\text{trace}(C)=1$ A leadfinla izanik, R iturrien kobariantza eta C zarataren kobariantza. Sraeko-erpin bakoitzeko denbora seriea MNE algoritmoa metodoa erabiliz kalkulatu zen, bai lambda eta lambda zarata hiruko balioa zutelarik. Azkenik, iturri denbora seriearen hiru momentuak erpin bakoitzeko norabide indartsuenera proiektatu ziren.*

Minimum Variance distortion-less response (MVDR, Van Veen et al., 1997, baita ere Beamformer bezala ezagututa) seinale prozesamendu alorretik neuroirudi domeinura moldatutako metodo bat da. Kokaleku bakoitzarentzat bariantza minimora mugatutako iragazki linearrak (linearly constrained minimum variance filters, LCMV) diseinatzen dira, kokaleku zehatz bateko burmuin aktibitate elektrikoa pasarazten duena beste kokalekuetakoa indargabetzen duen bitartean. Iragazki espazialak sensore mailako C kobariantza matrizearen azterna minimizatuz, $W^T A = I$ ekuazioa betetzen dutelarik kalkulatu dira (A leadfield matrizea eta W iragazkien matrizea). Iturri berreraikitze metodoen artean, beamformerra momentuko oszilazioetan erantzun indusituek edo faseari lotu gabeko erantzunek eragindako aldaketan kokalekua kalkulatzeko proposena da (Brookes et al., 2008).

Nola azaltzen da hau Metodoak atalean?

Beamformer iragazki espaziala erabili zen Van Veen et al. (1997). Horretarako, X-X Hz frekuentzia leihoa eta esperimentu osoa biltzen duen denbora leihok erabiliz datuen kobariantza matrizea kalkulatu zen. Erregularizazioa burutzeko Tikhonov metodoa aplikatu zen, erregularizatu gabeko matrizearen balio propio maximoaren % 5ko parametroa erabiliz. Boxelak burmuin osoa estaltzen zuen X mm-ko lauki-sare erregular (spatial grid) baten barruan definitu ziren eta joanerako modelo esfera-lokal-anitz metodoa erabiliz kalkulatu zen (Huang et al., 1999). Boxel bakoitzean banda zabaleko seinalko (X-15X0 Hz) beamformer iragazkiak kalkulatu ziren.

Analisi estatistikoak

Emaitzetan topatutako patroien eta egoeren arteko diferentzien esangura eta partaideen arteko konsistentzia aztertzeko analisi estatistikoak egiten dira, burmuin aktibitatearen modulazio zehatz bat azpimarratuz edo isolatuz. Neuroirudi domeinuan, ordea, arazo nagusi bat dago: konparazio anitzen arazoa. Zuzenketa metodo bat beharrezkoa da positibo faltsuak ekiditeko, negatibo faltsuen kopurua handitu gabe. Tesi honetan ausazko mulkoen permutazioa erabili da.

Ausazko mulkoen permutazioa(Maris and Oostenveld, 2007) aztertutako aldagaien maiztasun-banaketa inguruan auresuposatu gutxi egiten dituen metodo ez parametrikoa da. Hasteko, ohiko proba parametrikoko bat burutzen da (adibidez, t-proba) datu puntu guztietan. Estatistikoki esanguratsuak diren eta gertutasuna duten puntuekin mulkoak osatzen dira eta mulko bakoitzari balio estatistiko bat egokitzen zaio (clusterstat deitua). Tesi honetan, azkeneko hau mulkoaren balio estatistiko guztiak gehituz lortu da. Ondoren, permutazio bakoitzean prozedura

berdina errepikatzen da, partaideak ausaz nahastuta. Permutazio bakoizteko clusterstat handienarekin maiztasun-banaketa osatzen da. Azkenik, jatorrizko konparaketaren clusterstat balioa maiztasun-banaketarekin alderatzen da, jatorrizko konparaketaren esangura estatistikoa lortzeko.

Nola azaltzen da hau Metodoak atalean?

Egoeren arteko ezberdintasunak ausazko mulkoen permutazio analisia erabiliz aztertu ziren (Maris and Oostenveld, 2007). Bloke bakoitzean (aurre-proba, trebakuntza, orokortze-proba, etab.) urraketa-kontrol konparaketaren mulkoen estatistiken maiztasun-banaketa sortu zen. Sensore eta [-X X] s leiho tarteko puntu guztietan t-estatistikak kalkulatu eta algoritmoak sensore mulkoak topatu ziten denboran zehar. Bizilagun deskribapena Fieldtrip-ek eskainitako Neuromag-306 plantilan oinarritua zegoen. Datu puntu bat mulko baten parte izateko, $p < X$ (bi aldeko proba eta probabilitate zuzenketa erabiliz) ataka pasa eta gutxienez X bizilagun izan behar zituen. Mulko baten t-estatistikak gehiketa mulkoaren estatistika balio bezala hautatu zen (maxsum auekra Fieldtrip-en), eta X permutazioko ausazko proban erabili zen.

2.4 Laburpena

Kapitulu honetan aktibitate postsinaptikoak sortutako eremu magnetikoa MEGarekin nola neurtzen den deskribatu da. Gainera, 3,4 eta 5 kapituluetan datu analisietan erabilitako metodoak azaldu eta hauen adibideak eman dira.

II. Atala

Atal experimentalata

3. Kapitulu

Gramatika ikasketaren esperimentua

3.1 Oinarrizko arrazoia

Kapitulu honetan aurkeztutako esperimentuaren helburua gramatika arauak antzematen dituzten burmuin eremuak hobeto ezagutu eta deskribatzea da. Horretarako ama-hizkuntza gaztelania (Spanish, SP, H1) zuten partaideei Euskarazko (Basque, BQ, H2) gramatika arau bat erakutsi zitzairen trebakuntza aurretik, bitartean eta ondoren MEG seinaleak grabatu ziren. Jasotako sorrarazitako burmuin aktibitatearen iturri berreraikitzea aurkezten da ere.

Mueller-en arabera karga semantikoa murrizteak baliabideak libratu ditzake eta hauek urraketa sintaktikoen prozesamendurako erabili daitezke (Mueller et al., 2008). Hori dela eta, ariketan zehar aurkeztu ziren sintagmak Euskara-Gaztelera kognatuak diren izen eta adjektiboz osatuta zeuden, ikasketa prozesuan karga lexiko-semantikoa eta karga fonologikoa murrizteko, eta bide batez, mintzamenaren segmentazioa errazteko asmoarekin. Euskarak eta Gaztelarak inbentario fonologiko oso antzekoa dute eta, aldi berean, beraien sistema gramatikalak oso ezberdinak dira.

Egoera naturaletan ikasleek gaitasun gramatikala mintzamenaren eta ulermenaren bitartez ikasten dute. Egoera hauetan ematen den gramatika ikasketa hobeto imitatzeke, partaideek esaldiak gramatikalki zuzenak ziren erabaki zuten eta, baita ere, marrazki-deskribapen ariketa baten bitartez esaldien gramatika zuzena sortzen ikasi zuten. H2 ikasleak euskarazko ama-hiztunen talde ezberdin batekin konparatu ordez (Muellerren ikerketetan egin zen bezala), partaide talde berdinen H1 eta H2 burmuin erantzunak jaso egin ziren bi hizkuntzen arteko ezberdintasunak hobeto aztertzeke.

Hipotesi nagusia kognatu-hiztegia erabiltzeak gramatika arau berria azkar ikastea ahalbidetzen duela da. Neurofisiologikoki, hipotesia H1 erabiltzean rekrutatzen

diren sare neuronalak H2 berri baten ikasketan esplizituki inplikaturak daudela da. Hau da, behin araua ikasita eta denbora-errealeko sisteman barneratuta dagoenean, ezker-atzealde burmuin eremuak (H1 urraketen anplitude handiagoa erakusten dutenak) anplitude handiagoa erakutsiko dute H2 urraketen erantzunetan. Hala ere, H2 ikasketaren hasierako faseak MEGekin ikertu gabe daudenez, ezin dira H1 eremuak agertuko direla aurreuposatu eta, beraz, ez da egokia H1 eremuetara mugatzea.

3.2 Metodo eta Materialak

Adierazpen etikoa

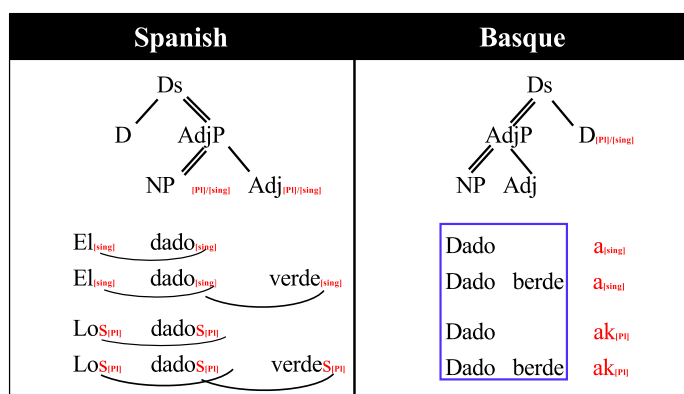
Ikerketa hau Basque Center for Cognition, Brain and Language-n egin da eta bertako etika komiteak onartua da.

Partaideak

Partaideak irakurketa eta entzumen arazorik ez zuten 17 (9 emakume, 8 gizon) Euskarazko jakintzarik gabeko Gaztelarazko ama-hiztun osasuntsu eta eskuinak izan ziren. Partaideak Donostialdean bilatu ziren. Esperimentua hasi aurretik, partaide guztiek idatzizko kontsentimendua eman zuten (Declaration of Helsinki) eta interferentzia magnetikoen bila miatuak izan ziren. 17 partaide hauetaz gain, bi partaide gehiagoren datuak jaso ziren, baina analisitik baztertuak izan ziren aginduak ez jarraitzeagatik.

Esperimentua

Esperimentu honetarako 'mini-Basque' deitu dugun euskara portzio zati txiki bat erabili dugu. Euskarak eta Gaztelarazko hiztegi zati esanguratsua elkarbanatzen dutela baina gramatika sistema oso ezberdinak dituztelaz baliatu gara esperimentu honetan. Partaideentzat ezagunak ziren hitzez baina gramatika arau berri batez osatutako euskarazko izen sintagmak erabili ziren estimulu gisa. Gaztelaniarekin antzerakotasun fonologikoa duten 80 izen eta lau adjektibo erabili ziren guztira (deskribapen fonologikoaren Levensthein distantzia: $m=0.77$; $std=1.4$ fonema). Aukeratutako gramatika araua (numero marka) nahikoa erraza da saio esperimental gutxiren baitan ikasteko modukoa. Numero gramatikala bi hizkuntzetan erabiltzen da baina modu ezberdinetan inplementatzen da, bi hizkuntzen sintagmen orden eta buru-sintagmen norabideagatik. Caffarra et al. (2015)-ren esanez numero inflekzioa 'ezberdin' inplementatzen da. 3.1. irudiak erakusten duen bezala, Gaztelaraz plurala



3.1. irudia: Euskarazko eta Gaztelerazko izen sintagmen numero inflekzio ezberdintasunak. Geziek numero marken arteko erlazioak adierazten dituzte, marra sinpleek dependentzia eta marra bikoitzek buru-dependentzia.

sintagmako elementu guztietan markatzen da. Bestalde, Euskaraz sintagmaren azkeneko elementuan markatzen da soilik.

Estimuluak

Esperimentua hiru izen-sintagma motaz osatua dago: kontrol sintagma, urraketa sintagma eta betetzaileak (ikus 3.1 taula).

3.1. irudiak eta 3.1. taulak erakusten duten moduan, Gazteleraz numero konmuztadura singtagmako elementu guztiak markatuz sortzen da; determinatzailea, izena eta adjektiboa: Los dados verdes. Gaztelerazko urraketa sintagma adjektiboaren numero marka okerra erabiliz sortu ziren, beraz, urraketa/kontrol puntua adjektiboaren bukaeratik gertu dator. Euskaraz, ordea, numero konmuztadura sintagmaren azkeneko elementuan markatzen da (esperimentu honetan izena edo adjektiboa izan daiteke): Dado berdeak. Urraketa sintagmetan morfema kritikoa izenari jarraitzen dion adjektiboaren lehenengo morfema da, hau da, numero inflekzioa duen izenaren ondoren datorren morfema. Partaideek inflekzioa duen izena agertzean zuzenean urraketa ez antzemateko, sintagma betetzaileak erabili ziren: izenez soilik osaturiko izen sintagma. Kasu honetan sintagmek determinatzailea eta izena zuten baina ez zuten adjektiborik. Horrela, partaideek erabakia hartu ahal izateko inflekzioa zuen izenaren ondoren ea adjektiborik zeterren entzutera itxoin behar zuten. Ez zen izen soltez osaturiko sintagmarik aurkeztu (dado), Euskaraz determinatzailea ez bait da aukerazkoa. Sintagma betetzaileak ez ziren analisirako kontuan hartu.

Ulermen proba/trebatze bloke bakoitza 184 entsaioz osatuta zegoen: 80 kontrol sintagma, 80 urraketa sintagma eta 24 sintagma betetzaile. Urraketa, kontrol

Egoera	Mini-Basque sintagmak	Gaztelera-zko sintagmak
Kontrol sintagmak	Dado[] berdea[Sing]	El[Sing] dado[Sing] verde [Sing]
	Dado[] berdeak[Pl]	Los[Pl] dados[Pl] verde s[Pl]
Urraketa sintagmak	*Dadoa[Sing] berdea[Sing]	*El[Sing] dado[Sing] verde s[Pl]
	*Dadoak[Pl] berdeak[Pl]	*Los[Pl] dados[Pl] verde [Sing]
Betetzaileak	Dadoa[Sing]	El[Sing] dado[Sing]
	Dadoak[Pl]	Los[Pl] dados[Pl]

3.1. taula: Adibide sintagmak. | urraketa eta kontrol puntuak adierazten ditu. Ezaugarri marka kortxete artean dijoa (e.g., [Pl] edo [Sing]), markatu gabeko ezaugarriak kortxete hutsekin adierazi dira: [].

eta sintagma betetzaileak ausaz nahastuta aurkeztu ziren bloke bakoitzean, baina zerrenda berbera aurkeztu zitzairen partaide guztiei. Bloke bakoitzak 15 minutu inguru iraun zituen.

Mini-Basque sintagmak gaztelera-ekin antzekotasun fonologikoa duten 80 izen eta 4 adjektibokin osatu ziren. Izen horietako 60 eta bi adjektibo trebakuntza blokeetan erabili ziren eta gainontzeko 20 izenak eta 2 adjektiboak orokortze blokeetan. Beraz, esperimentuan ez da sintagmarik errepikatu eta trebakuntza blokeetan aurkeztutako hitzak ez dira orokortze blokeetan ageri.

Estimuluak jaiotzez Euskara-Gaztelera elebiduna den emakume batek soinu-kabina batean grabatu zituen. Audioen anplitudea bolumen berdinerak ekuilazatu zen eta 60 Db tara aurkeztu ziren. Grabatutako estimuluaren luzerak bloke eta egoerako 3.2. taulan aurkitu daitezke.

Estimulu auditiboak erabili zirenez, entsaio bakoitzaren morfema kritikoaren agerpen denbora aldakorra da. Analisisetan puntu kritikoa zehazteko, Gaztelera-zko eta Euskerazko blokeen batezbesteko puntu kritikoa kalkulatu zen. Euskerazko sintagmentzat, bigarren hitzaren hasiera neurtu zen Praat softwarea erabiliz (Boersma and Weenik, 1990, version 5326), eta ondoren balio hauen batezbestekoa kalkulatu. Gaztelera-zko sintagmentzat, azken hitzaren amaiera neurtu zen (Praat erabiliaz ere) eta balioen batezbestekoa kalkulatu zen.

MEG grabaketan bitartean estimulu auditiboak panel bozgoragailuak erabiliz aurkeztu ziren (bi SSHP 60 x 60 panel; Panphonics Oy, Helsinki, Finlandia).

Blokea	Kontrol	Urraketa
Pre-Test BQ	1.32(0.23)	1.48(0.29)
Pre-Test SP	1.56(0.29)	1.61(0.26)
Training 1	1.42(0.32)	1.54(0.34)
Training 2	1.43(0.29)	1.60(0.38)
Training 3	1.41(0.28)	1.58(0.36)
Gen-Test BQ	1.43(0.25)	1.58(0.31)
Post-Test SP	1.61(0.29)	1.65(0.35)

3.2. taula: Estimuluen batezbesteko (desbideratze tipikoa) luzera segundutan blokeko.

Diseinua eta ariketak

Esperimientua bi egun jarraietan egindako bi saiotan banatuta dago. Bi eguneko diseinua aukeratzeko bi arrazoi nagusi zeuden. Lehenengoa, lehenengo egunenean ikusitako efektuak ea bigarren egunean mantentzen diren aztertu ahal izateko. Bigarrena, burmuinaren erantzunak trebakuntza bitartean nola aldatzen diren ikusi nahi bada, trebakuntza entsaio asko behar dira. Guztiak egun berdinean egingo balira esperimientua luzea eta neketsua bihurtuko zen. Lehenengo saioa zazpi blokez osatua dago: aurre-proba bat Euskaraz, aurre-proba bat Gazteleraz, arau azalpena, ulermenean trebakuntza, mintzamenean trebakuntza, beste trebakuntza bat ulermenean eta beste trebakuntza bat mintzamenean (ikus 3.2 irudia, 1. zutabea).

Ulermen ariketako entsaioetan atzeko-proiekzio pantaila batean finkatze-gurutze bat ageri zen bi segunduz, ondoren sintagma aurkezten zen bozgoragailuetatik. Finkatze-gurutzea pantailan mantentzen zen esaldi bitartean eta hau bukatzean galdera ikurra agertzen zen pantailan, eta bertan mantentzen zen partaideak erantzun bat eman edota denbora bukatu arte (4 segundu). Trebakuntza blokeetan, partaidearen erantzunari jarraituz erantzunaren zuzentasunari buruzko informazioa aurkezten zen pantailan: lauki berde (zuzena) edo gorri (okerra) bat. Partaideak erantzun bat baino gehiago emanaz gero, soilik lehenengo erantzuna ebaluatzen zen eta besteak baztertzen ziren.

Euskarazko aurre-proba partaideek euskarazko jakintzarik ez zutela bermatzeko eta estimuluak berak eragindako efekturik ez zegoela ziurtatzeko gauzatu zen.

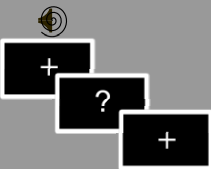
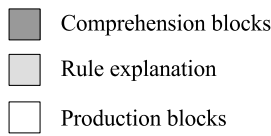
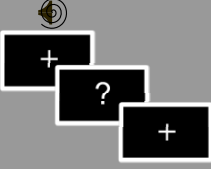
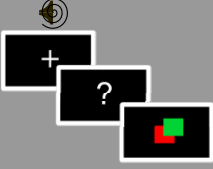
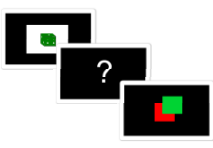
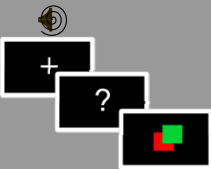
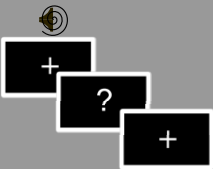
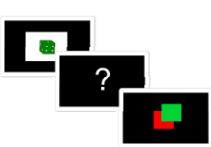
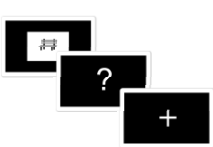

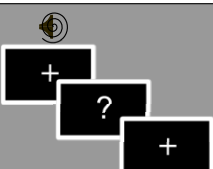
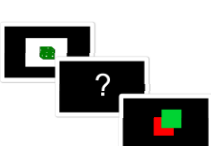
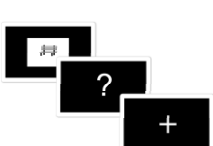
Aurre-proban partaideei Euskarazko esaldiak entzungo zituztela esan zitzairen eta entzuten zuten esaldia ea zuzena (botoi berdea sakatuz) edo okerra (botoi gorria sakatuz) zen adierazteko eskatu zitzairen. Gaztelerazko aurre-proba partaideen H1ean erreferentzia base bat neurtzeko egin zen. Partaideek botoi berdea sakatu behar zuten esaldi zuzenentzat eta botoi gorria esaldi okerrentzat. Ez euskarazko ez gaztelerazko aurre-probetan ez zen erantzunen zuzentasunari buruzko informaziorik eman. Lehenengo bi aurre-proben ondoren partaideei esan zitzairen ikerketaren beste zati guztia Euskarazko gramatika arau baten ikasketa bat izango zela. Araua azaltzeko 3.1. irudian agertzen den adibidea erabili zen. Partaideek nahi zituzten galdera haina egin zitzaizkien araua ondo ulertu zutela ziurtatzeko. Araua eta ariketak azaldu ostean, trebakuntza blokeak hasi ziren. Aurre-probaren antzera, partaideek sintagmak entzun eta zuzenak edo okerrak ziren erabaki behar zuten, baina trebakuntza blokeetan lauki berde edo gorriarekin emandako erantzunaren zuzentasuna adierazi zitzairen.

Mintzamen ariketa irudi-izendapen ariketa bat izan zen. Atzera-proiektzio pantaila batean partaideek finkatze-gurutze bat ikusten zuten bi segunduz, jarraian kolore bakarrean margotutako marrazki bat edo bi agertzen ziren (adibidez, dado berde bat, edo bi kotxe gris). Irudiaren ondoren, galdera ikurra ageri zen eta partaideek singularrean edo pluralean izen sintagma egokia sortu behar zuten. Emandako lehenengo erantzunean oinarrituta, pantailan agertutako lauki berde edo gorri bidez erantzunaren zuzentasuna adierazi zitzairen. Trebakuntza blokeetako mintzamen ariketak euskaraz burutu ziren.

Bigarren saioak sei bloke zituen: ulermenean trebakuntza, mintzamenean trebakuntza, ulermen orokortze proba bat, mintzamen orokortze proba bat, ulermen proba gazteleraz, mintzamen proba gazteleraz (ikus 3.2. irudia, 2. zutabea). Trebakuntza blokeek aurreko eguneko sekuentzia berdina jarraitzen zuten. Ulermen eta mintzamen orokortze probatan, trebakuntzaren sekuentzi berdina jarraitzen zuten, baina erantzunaren zuzentasunaren inguruko informaziorik eman gabe. Gainera, erabilitako estimulu sorta trebakuntzan erabilitakoaren ezberdina zen (aurreko atalean azaldu den bezala). Orokortze proben helburua partaideek gramatika araua ikasi edota sintagma solteak zuzenak edo okerrak ziren buruz ikasi zituzten aztertzea zen. Gaztelerazko blokeak, gazteleraz bigarren egunean erreferentzia base bat izateko erabili ziren.

Prozedura

Bi saioak bi egun jarraietan burutu ziren. Partaide bakoitzarentzat deskribatutako bloke guztiak grabatu ziren. Partaideei grabaketa bitartean postura eroso hartu eta

DAY 1		DAY 2											
	Pre-Training Test (Basque) - Judgement task - No feedback												
	Pre-Training Test (Spanish) - Judgement task - No feedback		Training 3 (Basque) - Judgement task - Visual feedback										
<table border="1"> <thead> <tr> <th>Spanish</th> <th>Basque</th> </tr> </thead> <tbody> <tr> <td>El... dado...</td> <td>Dado berde</td> </tr> <tr> <td>El... dado... verde...</td> <td>Dado berde</td> </tr> <tr> <td>Los... dados...</td> <td>Dado berde</td> </tr> <tr> <td>Los... dados... verdes...</td> <td>Dado berde</td> </tr> </tbody> </table>	Spanish	Basque	El... dado...	Dado berde	El... dado... verde...	Dado berde	Los... dados...	Dado berde	Los... dados... verdes...	Dado berde	Rule Explanation		Training 3 (Basque) - Picture naming - Visual feedback
Spanish	Basque												
El... dado...	Dado berde												
El... dado... verde...	Dado berde												
Los... dados...	Dado berde												
Los... dados... verdes...	Dado berde												
	Training 1 (Basque) - Judgement task - Visual feedback		Generalization Test (Basque) - Judgement task - No feedback										
	Training 1 (Basque) - Picture naming - Visual feedback		Generalization Test (Basque) - Picture naming - No feedback										
	Training 2 (Basque) - Judgement task - Visual feedback		Post-Training Test (Spanish) - Judgement task - No feedback										
	Training 2 (Basque) - Picture naming - Visual feedback		Post-Training Test (Spanish) - Picture naming - No feedback										

3.2. irudia: Ikerketaren diseinua. Ezkerreko zutabeak lehenengo saioaren eskema adierazten du, eskuinekoak bigarren saioarena (lehenengo eta bigarren saioa egun jarraitetan burutu ziren). Gris ilunez dauden blokeak, ulermen ariketak dira. Bloke txuriak mintzamen ariketak, eta gris argia arau azalpena.

erlaxatzeko eskatu zitzairen datu grabaketa bitartean mugimenduak ekiditeko asmoz. Ariketen bitartean begi, buru eta gorputz mugimenduak saihesteko eskatu zitzairen ere. Bi elektrokulograma (bertikala eta horizontala) eta elektrokardiograma simple bipolar bat jaso ziren ere, ondoren ICA bidezko artefaktu baztertzea gauzatu ahal izateko.

Buruaren forma digitalizatzeko Polhemus Isotrak (Polhemus, Colchester, VM, EEBB) boligrafo bat erabili zen. Buruaren forma digitala partaide bakoitzaren burua bere irudi estrukturalari (T1 irudia) lerrokatu ahal izateko erabili zen. Honetaz gain, partaidearen buruan buru-lokalizaziorako 5 espira kokatzen dira, eta hauen kokalekua fiduzialekiko jasotzen da. Bost espirak MEG grabaketa bitartean aktibo daude, buruaren lokalizazio jarraia ematen dutelarik (cHPI). MEG datuak Elekta ekipamendu batean berezko softwarean bidez, 1000 Hz lagintze-abiadura, 0.03 Hz goi-paseko iragazkia eta 330 Hzko behe-paseko iragazkia erabiliz jaso ziren.

Datu analisiak

Portaera analisiak

Ulermen ariketetako portaera datuak maila anitzeko erregresio lineal orokortua erabiliz modelatu ziren (Dixon, 2008). Modelorako bi faktore erabili ziren egoera (urraketa/kontrol) eta blokea(aurre-proba, trebakuntza 1...). maila anitzeko analisiak ematen dituen koefizienteak zailak dira ulertzeko, horregatik, koefizienteak zuzentasun proportzioetara itzuli ziren. Mintzamen ariketetako emaitzak antzera modelatu ziren, maila anitzeko erregresio lineal orokortua erabiliz (Dixon, 2008) baina soilik bloke faktorea erabiliz. Ikerketa honen helburua gramatika jabetza (eta ez lexiko jabetza) aztertzea denez, mintzamen ariketetan soilik gramatika izan zen zuzendua. Beraz, erantzun batek gramatika zuzena baina ahoskera edo adjektiboa guztiz ondo ez bazuen, erantzun zuzen bezala markatu zen. Hau da, partaideak Gaztelerazko kognatua erabiltzen bazuen baiian Euskarazko gramatika erantzun zuzena kontsideratzen zen.

MEG datuak

Ikerketa honen diseinuak ulermen eta mintzamen ariketak ditu. Partaideek araua zuzen ikasi dutela ziurtatzeko bi ariketa moten portaera emaitzak aurkezten dira. Hala ere, ikerketaren interesa gramatika epaiketean dagoenez MEG analisia soilik ulermen bloketan egin zen.

MaxFilter 2.2 erabilita MEG datuak Espazio Seinale Banaketa tenporalarekin (temporal Signal Space Separation tSSS) iragazki ziren lau segunduko denbora leihoa

eta 0.98ko korrelazio minimoa erabiliz. Partaide bakoitzaren buruaren jatorria eta sensore zaratatsuen zerrenda eskuz markatu ziren, datuen lagintze-abiadura 250 Hz-ra jaitsi zen eta linea elektrikoaren frekuentzia (50 Hz) eta honen harmonikoak iragazki ziren. MRC Cognition and Brain Science Unitek duen MEG laborategiaren gomendioak jarraituz, lagintze-abiadura jaitea eta iragazketa bi pausu ezberdinetan egin zen, softwareak duen akats baten ondorioz datuen kutsadura ekidizteko (http://imaging.mrc-cbu.cam.ac.uk/meg/Maxfilter_V2.2). Partaide bakoitzaren buruaren kokalekua, kokaleku lehenetsira transformatu zen, partaide eta blokeen artean buru kokaleku amankomuna zegoela ziurtatzeko. Batzbetse, lehen egunean buruen posizioak 20.4mm (std=6.65) aldatu ziren eta bigarren egunean 22.8 mm (std=5.01). Datuak Fieldtrip tresna erabiliz prozesatu ziren (20141202 bertsioa, Oostenveld et al., 2011). Lehenik, datuak segmentatuak izan ziren. Segmentuaren hasiera entsaioaren hasierakin lotu zen. Datuak 4 segunduko luzerako segmentutan banatu ziren, segundu 1 entsaio hasiera baino lehen eta 3 segundu hasieraren ostean.

Ondoren, artefaktuak bilatzeko datuak ikuskatu ziren: z-balioa 20 tik gora zuten segmentuak automatikoki baztertuak izan ziren. Segmentu bakoitza 12 segundutara iritsi arte zero-betegarriekin luzatu zen. 40 Hz-tan ezarritako behe-paseko FIR iragazki bat (zero-faseko pasada bakarra) erabili zen, eta 200 ms-ko (-200 - 0 ms) erreferentzia zuzenketa egin zen.

Datuak Konponente Independenteen Analisisa (ICA) algoritmoa erabiliz deskonposatu ziren. Konponente kopurua, gradiometro kopurura berdindu zen (204) eta analisi honen aurretik ez zen dimentsio murrizketa algoritmorik erabili. fastICA algoritmoa erabili zen konbinatu gabeko gradiometrotan (204 sensore). Ondoren, ICA konponente bakoitza HEOG; VEOG eta EKG seinaleekin korrelatu zen. Hiru desbideratze tipikotik gorako korrelazioa erakutsi zuten konponenteak baztertu egin ziren eta, ondoren, konponenteak jatorrizko sensore espaziora transformatu ziren.

Denborari-lotutako analisisa

Konbinatu gabeko sensoreetan egoera bakoitzeko (urraketa/kontrola) entsaioen batezbestekoa kalkulatu zen. Batezbestekoak kalkulatu ondoren, gradiometro planarrak konbinatu egin ziren. Soilik erantzun zuzenekin lotutako entsaioak erabili ziren gertaera bati lotutako eremuen (ERF) kontrasteetan, Euskarazko aurre-proban izan ezik. Bloke honetan partaideek erantzun zuzen gutxi zituzten eta nahikoa soinu-seinla ratioa (Signal to Noise Ratio, SNR) lortzeko entsaio guztiak erabili ziren (bloke bakoitzean erabilitako batezbesteko entsaio kopuruak 3.3 taulan aurkitu daitezke).

Egoeren arteko ezberdintasunak ausazko mulkoen permutazio analisisa erabiliz aztertu ziren (Maris and Oostenveld, 2007). Bloke bakoitzean (aurre-proba,

Block	Control	Violation
Pre-test BQ	77.8 (1.99)	78.7 (1.8)
Pre-Test SP	73.2 (7)	73.2 (7.4)
Training 1	72.8 (4.7)	70.5 (7.2)
Training 2	69.9 (18.5)	69.9 (18.7)
Training 3	76.4 (3.7)	72.7 (10.8)
Gen-test BQ	74.8 (3.6)	72.4 (6.6)
Post-test SP	73.8 (4.5)	69.1 (14.6)

3.3. taula: Analisisetan erabilitako bateztesbetko (std) ensaio kopurua bloke bakoitzeko.

trebakuntza, orokortze-proba, etab.) urraketa-kontrol konparaketaren mulkoen estatistiken maiztasun-banaketa sortu zen. Sensore eta [-0.2 2.5] s leiho tarteko puntu guztietan t-estatistikak kalkulatu eta algoritmoak sensore mulkoak topatu zituen denboran zehar. Bizilagun deskribapena Fieldtrip-ek eskainitako Neuromag-306 txantiloilan oinarritua zegoen. Datu puntu bat mulko baten parte izateko, $p < 0.05$ (bi aldeko proba eta probabilitate zuzenketa erabiliz) ataka pasa eta gutxienez bi bizilagun izan behar zituen. Mulko baten balore estatistiko bezala, mulko horretako t-estatistika guztien gehiketa hautatu zen (maxsum aukera Fieldtrip-en), eta 1000 permutazioko ausazko proban erabili zen.

Erraztasunagatik, emaitzen irudietan sensore guztien ERF uhinak azaltzen dira. Ondoan dagoen topografiak estatistikoki esanguratsua izan den denbora lehioan urraketa eta kontrol egoeren arteko diferentzia erakusten du. Sensore bat mulkoaren parte bazen leiho horren edozein momentutan (ez du leiho osoan zehar mulkoaren parte izan beharrik), asterisko batekin markatua da.

Iturri analisisia

Minimum Norm Estimate (MNE) (Dale et al., 2000) metodoa erabili zen. MRI egitura irudiak larruazal, gazezur, burmuin eta CSF mintzetan segmentatu zen, eta geruza bakarreko modeloa erabiliz burmuinaren bolumenari eroaltasun balio bat eman zitzaion. Bolumenaren eroaltasun modeloa eta geruza kanoniko kortikalean oinarritutako 5124-puntuko sarea (Fieldtripen eskuragarri) erabiliz leadfilak eraiki ziren. Alderantzizko emaitza kalkulatu aurretik, leadfilak txurituak

izan ziren. Iturrien kobariantza matrizea eskalatu zen ondorengo ekuazioa bete zezan: $\text{trace}(A^*R^*Aff)/\text{trace}(C)=1$ A leadfinla izanik, R iturrien kobariantza eta C zarataren kobariantza. Sareko-erpin bakoitzeko denbora seriea MNE algoritmoa metodoa erabiliz kalkulatu zen, bai lambda eta zarata-lambdahori hiruko balioa zutelarik. Azkenik, iturri denbora seriearen hiru momentuak erpin bakoitzeko norabide indartsuenera proiektatu ziren.

Denboran-mugatutako analisia

Sensoreetan ikusitako efektuetan ze burmuin eremuk egin duten ekarpena ikusteko, analisi estatistikoak iturri espazioan egin ziren ere. Iturri espazioan, ausazko mulkoen permutazio (500 permutazio) analisia erabili zen, sensore espazioan egin zen antzera (Maris and Oostenveld, 2007). Bloke bakoitzean (aurre-proba, trebakuntza, orokortze-proba, etab.) urraketa-kontrol konparaketaren mulkoen estatistiken maiztasun-banaketa sortu zen. Sare-erpin eta sensore mailan esanguratsua izandako denbora leiho tarteko puntu guztietan t-estatistikak kalkulatu eta algoritmoak erpin mulkoak topatu zituen denboran zehar. Bizilagun deskribapena distantzian oinarrituta kalkulatu zen, bi bizilagunen arteko distantzia maximoa 10koa izanik. Datu puntu bat mulko baten parte izateko, $p < 0.05$ (bi aldeko proba eta probabilitate zuzenketa erabiliz) ataka pasa eta gutxienez bi bizilagun izan behar zituen. Mulko baten t-estatistikak gehiketa mulkoaren estatistika balio bezala hautatu zen (maxsum aukera Fieldtrip-en), eta 500 permutazioko ausazko proban erabili zen.

Irudi sinpleak lortzeko asmoarekin, soilik esanguratsuek edo esanguratsu izatetik gertu zeuden burmuin eremuak agertzen dira irudietan. Mulko esanguratsuenik ez zuten blokeetan, p-balore baxuena zuen mulkoa irudikatu da datuen joera ikusi ahal izateko. Hala ere, jakitun gera bloke hauetako mulko ez esanguratsuen interpretazioa kontu handiarekin egin behar dela. Burmuin eremuak Fieldtrip-ek eskainitako AAL atlasean oinarrituta izendatu ziren: lehenik MNI espazioan definitutako AAL atlas analisian erabilitako sarera interpolatu zen. Ondoren mulko esanguratsu bakoitzarentzat maskara bat sortu zen eta maskaran dauden erpin horien izenak interpolatutako atlasetik jaso ziren.

Mugatu gabeko analisia

Iturri espazioan beste analisi estatistiko bat burutu zen. Lehenengo analisiak sensore analisian agertutako efektuen atzean dauden eremuak identifikatze balio duen bitartean, bigarren analisi honek sensore mailan jaso ez diren bestelako efektuak jasotzeko balio dezake.

Mugatu gabeko analisi honetan, ausazko mulkoen permutazio (500 permutazio) analisia erabili zen, sensore espazioan egin zen antzera (Maris and Oostenveld,

	Kontrol	Urraketa
Aurre-proba		
Gaztelera	0.95 (0.94, 0.96)	0.04 (0.02, 0.07)
Euskara	0.28 (0.21, 0.35)	0.67 (0.55, 0.77)
Trebakuntza		
1	0.95 (0.93, 0.97)	0.09 (0.05, 0.16)
2	0.97 (0.95, 0.98)	0.05 (0.02, 0.12)
3	0.99 (0.98, 1.00)	0.03 (0.01, 0.1)
Orokortze proba		
Euskara	0.99 (0.98, 0.99)	0.03 (0.01, 0.09)
Ondorengo-proba		
Gaztelera	0.98 (0.97, 0.99)	0.05 (0.01, 0.14)

3.4. taula: Zuzen emandako erantzunen proportzioa (%95) bloke bakoitzeko eta egoera bakoitzeko (urraketa/kontrola).

2007). Bloke bakoitzean (aurre-proba, trebakuntza, orokortze-proba, etab.) urraketa-kontrol konparaketaren mulkoen estatistiken maiztasun-banaketa sortu zen. Sare-erpin eta [-0.2 2.5]s leihotako puntu guztietan t-estatistikak kalkulatu eta algoritmoak erpin mulkoak topatu zituen denboran zehar. Bizilagun deskribapena distantzian oinarrituta kalkulatu zen, bi bizilagunen arteko distantzia maximoa 10koa izanik. Datu puntu bat mulko baten parte izateko, $p < 0.05$ (bi aldeko proba eta probabilitate zuzenketa erabiliz) ataka pasa eta gutxienez bi bizilagun izan behar zituen. Mulko baten t-estatistikak gehiketa mulkoaren estatistika balio bezala hautatu zen (maxsum aukera Fieldtrip-en), eta 500 permutazioko ausazko proban erabili zen. Nahiz eta emaitzen atalean emaitza guztiak azalduko diren (informaziorik ez ezkutatzeko), Guthrie eta Buchwald (1991)-en oinarrituta eztabaida atalak ez ditu kontuan hartu 10 puntu jarraian baino gutxiago irauten duten mulkoak (hau da, 40 ms). Muga hau erabili izan da EEG literaturan (Murray et al., 2001; Molholm et al., 2002; Kecskés-Kovács et al., 2013; Berger et al., 2014). Irudi sinpleak lortzeko asmoarekin, soilik esanguratsuak edo esanguratsu izatetik gertu zeuden burmuin eremuak irudikatu dira. Mulko esanguratsuenik ez zuten blokeetan, p-balore baxuena zuen mulkoa irudikatu da datuen joera ikusi ahal izateko.

	Singularra	Plurala
Trebakuntza		
1	0.96 (0.94, 0.98)	0.97 (0.91, 0.99)
2	0.98 (0.97, 0.99)	0.98 (0.94, 1.00)
3	0.99 (0.98, 1.00)	0.99 (0.93, 1.00)
Orokortze proba		
Euskara	0.99 (0.98, 1.00)	0.99 (0.89, 0.99)
Post-test		
Gaztelera	1.00 (0.99, 1.00)	0.99 (0.92, 1.00)

3.5. taula: Zuzen emandako erantzunen proportzioa (%95) bloke bakoitzeko eta egoera bakoitzeko (aingularra/plurala).

3.3 Emaidzak

Portaera analisisia: Ulermen trebakuntza eta proba

3.4. taulak bloke bakoitzean, egoera bakoitzeko (kontrol/urraketa), zuzen emandako erantzunen proportzioak (%95 CI) adierazten ditu. Euskarazko aurre-proban kenduta, bloke guztietan partaideek bi sintagma motak modu egokian bereizi zituzten. Gramatikalki zuzen ziren estimuluak 0.95-ko baino ratio altuagoarekin identifikatu eta ia urraketa gehienak baztertu zituzten. Euskarazko aurre-proban, ordea, gramatikalki zuzenak ziren sintagmetatik soilik 0.28a antzeman zituzten eta okerrak ziren sintagmen 0.67a zuzenak bezala klasifikatu zituzten. Ondorioz, partaideen erantzunen asmatze kopurua zorian izan daitekeena baino baxuagoa izan zen, beste blokeetan ia goi-muga jotzen duen bitartean (emaitza hauek 3.4 atalean sakon eztabaidatzen dira).

Portaera analisisia: Mintzamen trebakuntza eta proba

3.5. taulak bloke bakoitzean, egoera bakoitzeko (singularra/plurala), zuzen emandako erantzunen proportzioak (%95 CI) adierazten ditu. Bloke guztietan, partaideek gramatikalki zuzen edo oker bezala katalogatu ziren sintagmak sortu zituzten. Sintagmak katalogatzeko soilik gramatika izan zen kontuan, eta mintzameneko beste aspektuak (ahoskera, lexikoa...) baztertu ziren. Bai sintagma singularrak eta bai sintagma pluralak 0.96-ko ratioarekin zuzenki sortu zituzten (ikus 3.5 taula).

MEG datuak: Ulermen trebakunzta eta proba

Denborari-lotutako analisia

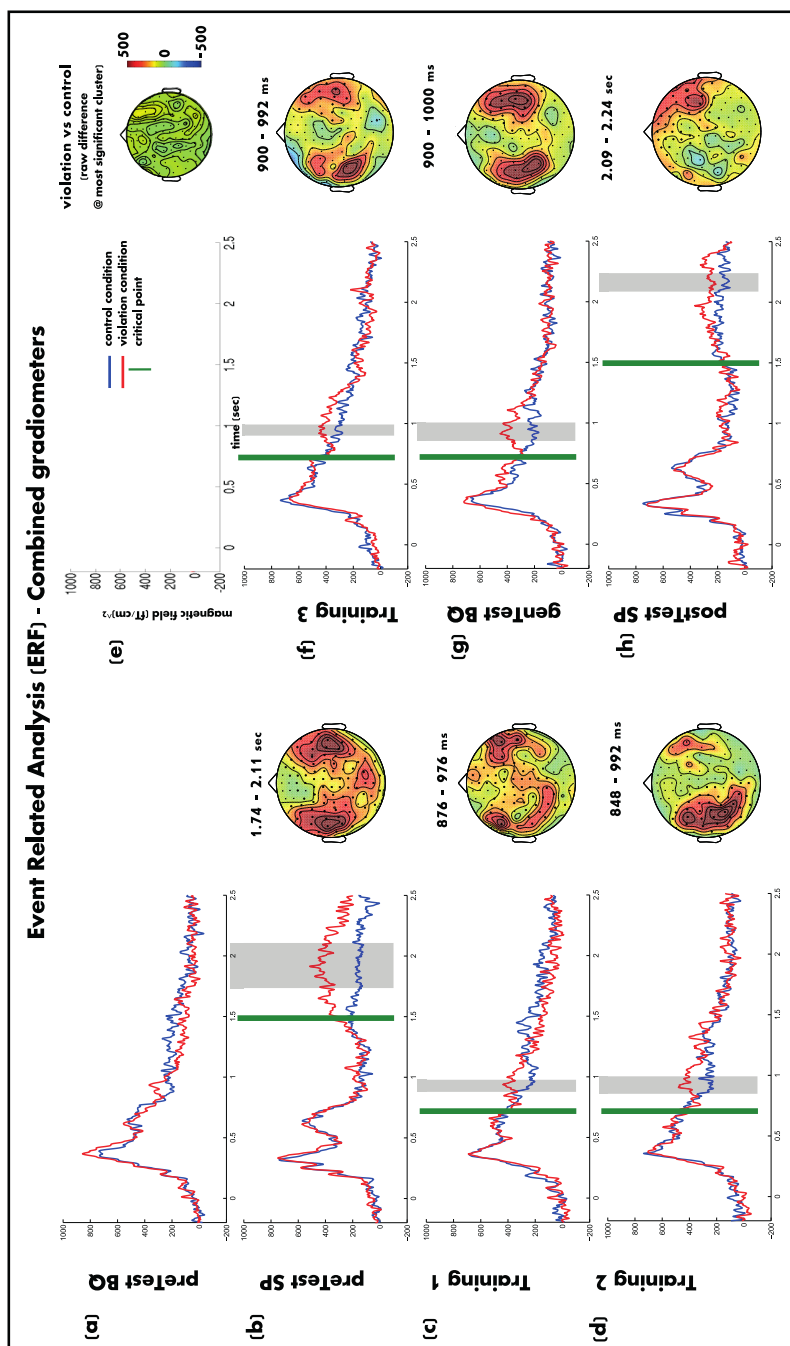
3.3. irudiak ERF analisiaren emaitzak irudikatzen ditu (bloke bakoitzean erabilitako entsaio kopuruak 3.3 taulan agertzen dira). Gaztelerazko aurre-proban (3.3b irudia) urraketa eta kontrol sintagmen hasieran ez da ezberdintasunik ageri. Soilik puntu kritikoa igarotzean hasten dira ezberdintzen bi egoerak, urraketa sintagmek anplitude handiagoko erantzuna dutelarik. Bi egoeren arteko ezberdintasunak segundu 1 inguruko iraupena du. Hala ere, analisi estatistikoak ezberdintasuna denbora leiho txikiago batean sostengatzen du soilik. Analiaren emaitzetan mulko bat ageri da puntu kritikoa pasa eta 240 eta 600 ms artean. Mulkoak bi hemisferioetako atzekaldeko sensore eta sensore tenporalez osatua dago (clusterstat=6686; $p<0.002$).

3.3a irudiak Euskarazko aurre-proban bai urraketa eta bai kontrol sintagmentzat antzeko erantzunak egon zirela erakusten du. Anali estatistikoak ez du mulko esanguratsurik topatu (clusterstat<250; $p>0.2$).

Trebakunzta blokeei dagokienez, hiru blokeetan urraketa eta kontrol sintagmen erantzunek ez dute puntu kritikoa baino lehenago ezberdintasunik erakusten. Puntu honen ondoren urraketa sintagmek anplitude handiagoko erantzunak erakusten dituzte eta ezberdintasun honek 100 ms inguru irauten ditu. Denbora domeinuan hiru blokeek erantzun antzekoak erakusten dituzten arren, domeinu espazialean blokeetan zehar bilakaera bat dago. Lehenengo trebakunzta blokean (ikus 3.3c irudia) efektua ia sensore guztietan zehar banatua dago, egoeren arteko diferentzia handiena eskuin sensore-frontalez eta ezker atze-tenporal sensorez osatutako talde batean aurkitzen delarik, puntu kritikoa pasa eta 29 eta 126 ms artean (clusterstat=966.5; $p=0.004$). Bigarren trebakunzta blokean (ikus 3.3d irudia), efektua ez zegoen hain sakabanatua eta nagusiki ezker hemisferioan ageri zen, puntu kritikoa pasa eta 0 eta 142 ms artean (clusterstat=1422; $p=0.002$). Azkenik, hirugarren trebakunzta blokean efektua ezker eta eskuin sensore tenporaletan kokatu zen puntu kritikoa pasa eta 50 eta 142 ms artean (clusterstat=375.5; $p=0.048$).

Euskarazko orokortze proban (ikus 3.3g irudia) topatutako erantzuna hirugarren trebakunzta blokean topatutakoaren oso antzekoa da: efektuaren magnitudea mantendu egin zen eta efektuaren topografiak bi hemisferioetako sensore tenporalak hartzen zituen. Anali estatistikoak eskuin sensore temporalez osatutako mulko esanguratsu bat erakutsi zuen puntu kritikoa pasa eta 50 eta 150 ms artean (clusterstat=1220; $p=0.008$).

Azkenik, Gaztelerazko ondorengo-probak (ikus 3.3h irudia) Gaztelerazko



3.3. irudia: Marraztutako uhinek sensore guztien batazbesteko ERFak irudikatzen dituzte, lauki grisek mulkoa estatistikoki esanguratsua diren denbora leihoak adierazten dituzte eta topografiek denbora-leiho horretan ematen den urraketa eta kontrol egoeren arteko diferentzia gordina irudikatzen dute. Irudi sinpleak lortzeko asmoarekin, p-balore baxuena duen mulkoa aurkezten du. Uhin urdinak, kontrol egoerari dagozkie, uhin gorriak urraketa egoerari eta marra berdeak puntu kritikoari dagozkie. Blokeak burutu egin ziren ordenean agertzen dira (a-h), irudien eskalak azaltzen direlarik (e).

aurre-probaren patroia ezberdin bat erakutsi zuen. Bi egoeren arteko diferentzia aurre-proban baina beranduago ageri zen eta diferentziaren magnitudea txikiagoa zen. Gainera, diferentzia topografia nahiko sakabanatua izan arren, diferentzia eskuin kopeta-sensoreetan kokatu zen. Analisi estatistikoak deskribatutako efektuarekin bat egiten zuen mulko esanguratsu bat azaltzen du, puntu kritikoa pasa eta 586 eta 736 ms artean, bereziki eskuin aurrealdeko sensoreez osatua (clusterstat=1514; $p < 0.002$).

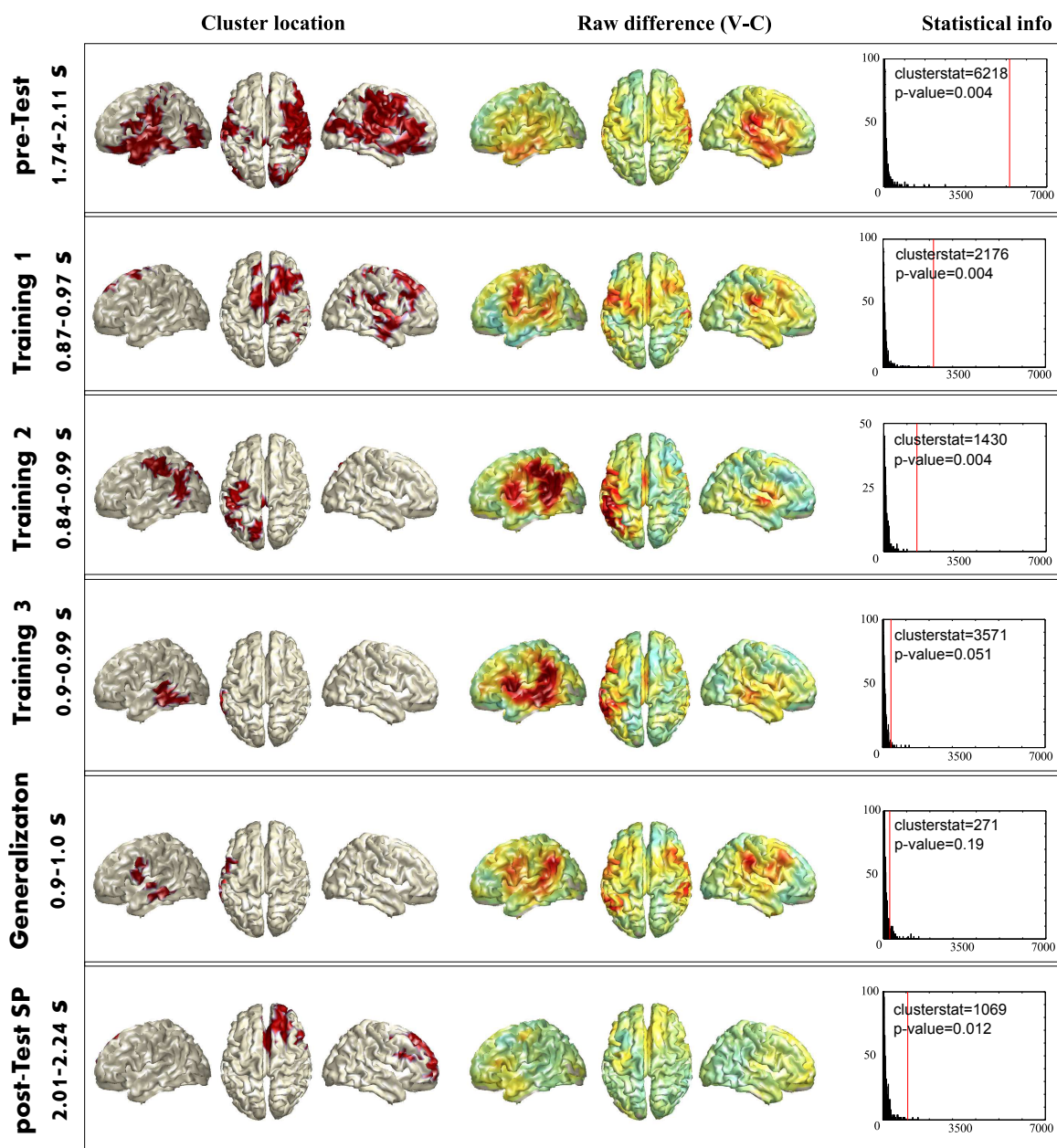
Iturri analisia

Denboran mugatutako analisia

3.4 irudiak denboran mugatutako (MNE iturri berreraikitzearen emaitzen) iturri analisi estatistikoaren emaitzak laburbiltzen ditu. Bloke bakoitzaren izen azpian ageri diren zenbakiak analisia mugatzeko erabilitako denbora-leihoak adierazten dituzte (sensore analisian oinarrituta). Lehenengo zutabeak mulkoaren iturri kokalekuak erakusten ditu. Erdiko zutabeak, denbora leiho horretan iturri mailan kontrol eta urraketa egoeren diferentzia gordina erakusten du. Eskubiko zutabeak mulkoaren informazio estatistikoa irudikatzen du. Burmuin eremu guztien izenak AAL atlasetik jasoak dira.

Gaztelarazko aurre-proban (ikus 3.4 irudiko lehenengo laukia), urraketa eta kontrol sintagma konparatzen dituen analisi estatistikoak bilateralki sakabanatutako sare batez osatutako mulko estatistikoki esanguratsu bat erakusten zuen (clusterstat=6218; $p=0.004$). Burmuin sareak eskuineko goikalde motor eremua, eskuin goi-aurrealdeko eremua eta bi hemisferioetako lobulu parietala (goi-parietal zirkunboluzioa eta arteka zentralaren aurre eta ondorengo zirkunboluzioak), lobulu frontala (orbitalis, opercularis eta triangularis), lobulu tenporala (Heschl zirkunboluzioa, erdi eta goi zirkunboluzio tenporalak eta erdi eta goi polo tenporalak), parieto-okzipital eremuak (zirkunboluzio angularra eta supramarginala), fusiformea eta erdialdeko lobulu okzipitalak jasotzen ditu. Mulko honek sensore domeinuan topatutako topografia sakabanatuarekin bat egiten du.

Euskarazko lehenengo trebakuntza blokean (ikus 3.4 irudiko bigarren laukia), analisi estatistikoak nagusiki eskuin hemisferioan kokatutako mulko esanguratsu bat (clusterstat=2176; $p=0.004$) adierazten du. Mulkoa lobulu parietalaz (goikalde motor eremu eta arteka zentralaren aurre eta ondorengo zirkunboluzioak), lobulu frontalaz (erdi eta goi zirkunboluzioak, triangularis eta opercularis), parieto-okzipital eremuez (zirkunboluzio angularra eta supramarginala), lobulu tenporalaz (Heschl zirkunboluzioa, erdi, behe eta goi zirkunboluzio tenporalak eta goi polo tenporala),



3.4. irudia: Denboran mugatutako analisiaren laburpena. Lauki horizontal bakoitzak bloke horren mulko esanguratsua erakusten du (bloke batek mulko esanguratsurik ez duenean, p-balore baxuena duen mulkoa erakusten da). Ezkerreko zutabeak mulkoaren iturri kokalekuak erakusten ditu. Erdiko zutabeak, denbora leiho horretan iturri mailan kontrol eta urraketa sintagmen diferentzia gordina erakusten du. Eskubiko zutabeak mulkoaren informazio estatistikoa irudikatzen du: urdinez ausazko maiztasun-banaketa, eta marra gorriak mulko horren clusterstat balioa adierazten du.

fusiformeaz eta ezker goi motor eremuaz osaturik dago. Patroi hau sensore mailan egindako analisisian topatutako patroiarekin bat dator.

Bigarren trebakuntza blokeari dagokionez (ikus 3.4 irudiko hirugarren laukia), analisi estatistikoak nagusiki ezker hemisferioan osatutako mulko estatistikoki esanguratsu bat (clusterstat=1430; $p=0.004$) azaltzen du. Mulkoak ezker lobulu parietala (goi parietal eremua eta arteka zentralaren aurre eta ondorengo zirkunboluzioak), lobulu tenporala (behe, erdi eta goi zirkunboluzioak), parieto-okzipital eremuak (zirkunboluzio angularra eta supramarginala), eremu goi-okzipitala eta fusiformea biltzen ditu. Patroi honek ere sensoreetan topatutako efektuaekin bat egiten du.

Hirugarren trebakuntza blokean (ikus 3.4 irudiko laugarren laukia), analisi estatistikoak urraketa eta kontrol sintagmen arteko diferentzia ezker hemisferioan osatutako eta estatistikoki ia esanguratsua den mulko batean kokatzen du (clusterstat=357, $p=0.051$). Mulko honek ezker lobulu tenporala (behe, erdi eta goi zirkunboluzioa), fusiformea eta behe zirkunboluzio okzipitala biltzen ditu. Kasu honetan sensore eta iturri analisiaren artean desadostasun txiki bat dago. Sensore mailako topografiak efektua bi hemisferiotako sensore tenporaletan kokatzen du, baina sensore mailako analisi estatistikoak mulkoa eskuin sensoreetan azaltzen duen bitartean iturri mailako analisi estatistikoak ezker hemisferioko ermeutan kokatzen du efektua.

Orokortze probari dagokionez (ikus 3.4 irudiko bostgarren laukia), ez da mulko estatistikoki esanguratsurik topatu. Hori dela eta, bloke honetan egon litezkeen efektuen joerak ulertu ahal izateko, esanguratsu izatetik gertuen dagoen mulkoa deskribatzen da hemen (clusterstat=271; $p=0.19$). Mulko hau ezker lobulu parietalaz (opercularis eta arteka zentralaren aurre eta ondorengo zirkunboluzioak) eta ezker goi motore eremuaz osatua dago. Patroi hau sensore mailan topatutakoarekin bat dator, baina, iturri mailako mulkoa ez da estatistikoki esanguratsua, beraz, interpretazioa kontu handiarekin egin behar da.

Gaztelerazko ondorengo-probari dagokionez (ikus 3.4 irudiko seigarren laukia), analisi estatistikoak nagusiki eskuin hemisferioan osatutako mulko bat azaltzen du (clusterstat=1069; $p=0.012$). Mulkoa eskuin lobulu parietala (arteka zentralaren aurre zirkunboluzioa eta goi motor eremua), lobulu frontala (opercularis, triangularis, orbitalis eta goi zirkunboluzio frontala) eta ezker goi motor eremuak bitzen ditu. Patroi hau sensore mailan topatutako patroiarekin bat egiten du, nahiz eta Gaztelerazko aurre-proban topatutako efektuen patroia ezberdina den.

Mugatu gabeko analisisia

3.5. irudiak mugatu gabeko analisi estatistikoaren emaitzak laburtzen ditu 3.4. irudiaren eskema berdina jarraituz. Hala ere, atal honek ez ditu emaitzak sensore mailarekin konparatzen.

Gaztelerazko aurre-proban (ikus 3.5 irudiko lehenengo laukia), analisi estatistikoak estatistikoki esanguratsuak diren bi mulko erakusten ditu. Lehenengo mulkoa (clusterstat=12614; $p=0.004$) 1.84 eta 2.01 s artean agertzen da eta eskuin parietal lobuluan (supramarginala eta arteka zentralaren aurre eta ondorengo zirkunboluzioetan) eta lobulu tenporaleko goi zirkunboluzioan kokatzen da. Bigarren mulkoa (clusterstat=5619; $p=0.008$) 1.484 eta 1.612 s artean agertzen da ezker lobulu parietalean (behe parietal eremuan eta arteka zentralaren ondorengo zirkunboluzioan).

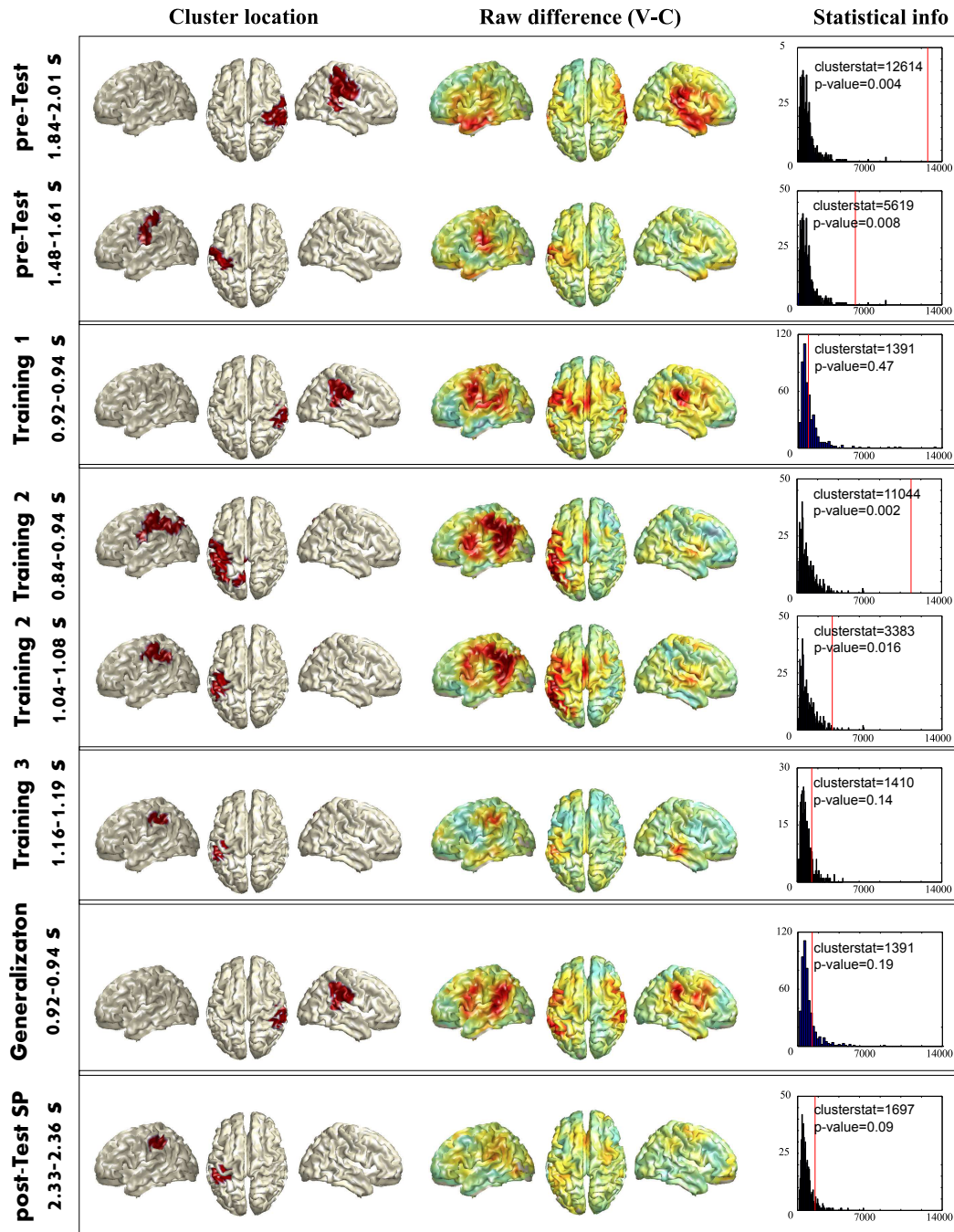
Lehen trebakuntza blokean (ikus 3.5 irudiko bigarren laukia), mugatu gabeko analisi estatistikoak ez zuen mulko estatistiko esanguratsurik topatu. Esanguratsua izatetik gertuen topatutako mulkoa (clusterstat=1391; $p=0.47$) 924 eta 940 ms artean topatu zen eskuin behe lobulu parietalean (supramarginala, arteka zentralaren aurre eta ondorengo zirkunboluzioetan) eta goi zirkunboluzio tenporalean.

Bigarren trebakuntza blokean (ikus 3.5 irudiko hirugarren laukia), estatistikoki esanguratsuak diren bi mulko topatu ziren. Lehenengo mulkoa (clusterstat=11044; $p=0.002$) 844 eta 944 ms artean topatu zen ezker lobulu parietalean (supramarginala eta arteka zentralaren aurre eta ondorengo zirkunboluzioetan) eta ezker zirkunboluzio angularrean. Bigarren mulkoa (clusterstat=3383; $p=0.016$) 1.044 eta 1.08 s artean topatu zen ezker behe parietal eremuan, supramarginalean eta zirkunboluzio angularrean.

Hirugarren trebakuntza blokean (ikus 3.5 irudiko laugarren laukia), ez zen mulko estatistikoki esanguratsurik topatu. Esanguratsua izatetik gertuen zegoen mulkoa (clusterstat=1410; $p=0.14$) 1.16 eta 1.19 s artean agertu zen ezker lobulu parietalean (behe parietal eremua, supramarginala eta arteka zentralaren ondorengo zirkunboluzioan).

Orokortze-probako blokean (ikus 3.5 irudiko bosgarren laukia), analisiak ez zuen estatistikoki esanguratsua den mulkorik erakutsi. Esanguratsua izatetik gertuan zegoen mulkoa (clusterstat=1391; $p=0.19$) 924 eta 940 ms artean topatu zen eskuin lobulu parietalean (behe parietal eremua, supramarginala eta arteka zentralaren ondorengo zirkunboluzioan).

Azkenik, Gaztelerazko ondorengo-proba blokean (ikus 3.5 irudiko seigarren laukia), estatistikoki marjinalki esanguratsua den mulko bat (clusterstat=1697;



3.5. irudia: Mugatu gabeko analisiaren laburpena. Lauki horizontal bakoitzak bloke horren mulko esanguratsua erakusten du (bloke batek mulko esanguratsurik ez duenean, p-balore baxuena duen mulkoa erakusten da). Ezkerreko zutabeak mulkoaren iturri kokalekuak erakusten ditu. Erdiko zutabeak, denbora leiho horretan iturri mailan kontrol eta urraketa sintagmen diferentzia gordina erakusten du. Eskubiko zutabeak mulkoaren informazio estatistikoa irudikatzen du: urdinez ausazko maiztasun-banaketa, eta marra gorriak mulko horren clusterstat balioa adierazten du.

$p=0.09$) agertzen da 2.33 eta 2.36 s artean ezker lobulu parietalean (behe parietal eremua, supramarginala eta arteka zentralaren ondorengo zirkunboluzioan).

Bi iturri analisisien laburpena

Orokorrean, mugatu gabeko analisi estatistikoak denboran-mugatutako analisiak baino indar estatistiko txikiagoa du. Gainera, bi analisisietako mulkoak zuzenki konparatuz gero, patroï batzuk antzekoak kontsideratu daitezkeen arren mulko gehienek ez dute bat egiten. Irakurleak pentsa dezake bi analisisiek behaketa ezberdinak irudikatzen dituztela eta bata edo bestea aukeratzen lagunduko digun neurgailu bat beharko genukeela. Bi analisisetan lortutako mulkoak sensore mailan topatutako efektuekin konparatzen ditugunean, ordea, mulko guztiak diferentzia gordinaren patroï zati batekin bat egiten dute. Horregatik, analisi bakoitza urraketa-kontrol efektuaren zati ezberdin bati sentikorra dela gerta daitekeela uste da. Ondorioz, bi analisisiek osagarriak diren emaitzak ematen dizkigute, ariketa honen atzean dauden prozesu neuronalak hobeto ulertzeko aukera ematen dutelarik.

3.4 Eztabaida

Hemen azaldutako esperimentuak, ikasle helduek trebakuntza saio eta orokortze probatan gramatika portzio baten numero konmuztadura morfosintaktikoari lotutako ERF uhinak eta hauen iturri kokalekuak ikertzen ditu. Orokorrean, emaitzek ERF uhinak azkar aldatu daitezkeela erakusten dute eta Euskarazko kontrol eta urraketa sintagmen arteko bereizketa trebakuntza ordu gutxien baitan agertu daitekeela erakusten dute. Burmuin osoko analisia irizpide bezala hartuta, urraketa-sintagmen erantzunak ama hizkuntzan erabiltzen diren burmuin eremu antzekoetan agertzen da. Hurrengo azpiataletan blokez bloke eztabaidatzen dira aurkitutako emaitzak eta azkenik eztabaida orokor bat probesten da.

Euskarazko aurre-proba

Partaideek aurre-proban sintagma zuzenak eta okerrak bereizteko zuten gaitasuna zori maila azpitik zegoen: joeraren bat zuen ausaz erantzuten zuten edo sitematikoki estimuluak alderantziz klasifikatzen zituzten. Hasiara batean partaideek zori maila azpitik egoteak logikarik ez duen arren, badirudi partaideek estimuluak azaleko morfologia (eta ez arau morfologikoa) erabiliz klasifikatu zituztela. Guztiz espekulatiboa den arren, izan daiteke Gaztelaniazko ama-hiztunek sintagma bat gramatikalki zuzena bezala onartzea soilik Euskarazko berezko morfologia inflekzioa duelako ('-a' edo '-ak'). Hala ere, ERF uhinetan bi sintagma moten artean

ezberdintasunik ez topatzeak, estimuluen izaera fisikoak (fonologia, prosodia, etab.) sintagmak ezberdintzeko pistarik ematen ez dutela adierazten du.

Gaztelera-zko aurre-proba

Espero zen bezala, bloke honetako erantzunak goi-mugatik gertu zeuden, partaideek ariketari eta azalpenei kasu egiten zieten konfirmatuz. Bi sintagma motekin, urraketa eta kontrol sintagmekin, sorrarazitako ERF uhinek sensore-topografia eta denbora-serie antzekoa zuten, urraketa sintagmekin ERFak anplitude handiagoa zuelarik. Urraketa eta kontrol egoerek ez zuten estatistikoki esanguratsua den ezberdintasunik erakutsi puntu kritikoa pasa eta 240 ms pasa arte. orduan urraketa egoeraren erantzuna indartsuagoa zen segundu batez. Diferentzia nagusiki bi hemisferiotako sensore tenporaletan topatu zen, naiz eta sensore parietal eta okzipital batzuetan ere ageri zen. Sensore-mailako analisiarekin bat eginez, iturri mailako analisisiek efektua nagusiki bi hemisferioetakoa lobulu parietal eta tenporaletan kokatu zuten.

Trebakuntza

Partaideek sintagmak ezberdintzeko gaitasun handia erakutsi zuten lehenengo trebakuntza bloketik hasita, portaera aldaketa honekin bat egiten zuten ERF diferentziak topatu ziren urraketa eta kontrol entsaiotan. Trebakuntzako hiru blokeetan, efektuaren hasiera (puntu kritikoa erreferentzia bezala hartuta) Gaztelera-zko blokean baino lehenago agertu zen, eta efektuaren iraupena ere motzagoa izan zen (150 ms trebakuntza blokeetan eta 360 ms Gaztelera-zko blokean). Trebakuntza bloketik blokeera efektuaren kokalekua aldatu zen.

Portaera emaitzetan oinarrituta, lehenengo bloketik erantzunak goi-mugan zeudenez, ikasketa jada gertatu dela pentsa daiteke eta, beraz, hurrengo trebakuntza blokeek ez dutela ikasketarik isladatzen ondorioztatu daiteke. Hala ere, jakintza bat izan eta jakintza hau esaldiak garatzen diren bitartean denbora errealean erabiltzea gauza bera direla pentsatzea da hau. Uste honen kontra, ordea, ikasleek arauetan oinarritutako jakintza hizkuntzaren denbora errealeko prozesamendura pasa arte denbora behar dutela erakutsi da lehenagotik (McLaughlin et al., 2010).

Lehenengo trebakuntza blokean efektua nagusiki eskuin sensore parietalean topatu zen, nahiz eta ezker sensore tenporal eta atzekaldeko sensore gutxi batzuetan ere ageri zen. Iturri mailako bi analisisiek efektua nagusiki eskuin lobulu fronto-parietalean eta lobulu tenporalean kokatua dagoela adierazten dute. Bigarren trebakuntza blokeari dagokionez, efektua nagusiki ezker hemisferioko sensoreetan

eta eskuin sensore frontal batzuetan aurkitu zen. Iturri mailako analisiak honekin bat egiten duen patroia bat azaldu zuen. Iturri mailan, urraketa egoerak erantzun indartsu bat sorrarazi zuen ezker lobulu tenporal eta parietaletan, eta erantzun apalago bat lobulu okzipitalean. Hirugarren blokean, bigarren blokearen antzera, efektua nagusiki bi hemisferiotako sensore tenporaletan topatu zen. Bloke honetako topografiak, Gaztelerazko aurre-proban aurkitutako topografia gogorarazten du. Bi iturri analisek efektua ezker lobulu tenporalean, behe-zirkunboluzio okzipitalean eta fusiformean kokatzeko joera estatistikoa dute. Hala ere, emaitza hauek marjinalki esanguratsuak dira eta tentuz ibili behar da interpretazio bat ematerakoan. Kasu honetan gainera, sensore mailako analisiarekin desadostasun txiki bat dago. Sensore mailako topografiak bi hemisferiotako sensore tenporaletan kokatzen du efektua. Analisi estatistikoak efektua eskuin sensoreetan babesten duen bitartean, iturri mailako analisiak ezker hemisferioko eremuak azaltzen ditu.

Lehenengo trebakuntza blokeko efektua eskuin eremu frontaletan kokatu zen. Eremu hau akats-sintaktikoetara mugatzen ez den akats antzemateekin lotua izan da lehenagotik (Indefrey et al., 2001). Gainera, HERA modeloan arabera (Habib et al., 2003), eskuin kortex aurrefrontala oroimen berreskuratzearekin lotua dago eta ezker kortex aurrefrontala oroimen kodetzearekin. Bloke honetako efektu nagusia eskuineko eremu frontaletan topatzeak, gramatika ikasketaren hasierako faseetan gramatika epaiketaren oroimen berreskuratze prozesua tartean dela adierazi dezake.

Bigarren trebakuntza blokean efektua ezker-lateralizatua dago nahiz eta eskuineko sensore frontal batzuek urraketa eta kontrol egoeren arteko diferentzia erakusten duten ere. Hirugarren blokeko sensor-mailako topografiak efektua bi hemisferiotako sensore tenporaletan kokatzen ditu, Gaztelerazko aurre-probaren antzera. Iturri analisisian emaitzak ikusterakoan, bigarren blokearen antzera, efektua hizkuntza sarean kokatzen da baina patroia Gaztelerazko aurre-probakoren ezberdina da (gogoratu Gaztelerazko aurre-probak efektua bi hemisferioetan kokatzen duela). Aurretik egin diren fMRI ikerketengatik badakigu eremu hauek mintzamenaren ulermenean parte hartzen duen hizkuntza sarearen parte direla (Friederici, 2011). Honen antzera, Davidsonek Holandesa ikasten zuten alemaniarren sintagmen-orden urraketekin lotutako MEG erantzunak ikertu zituen (Davidson and Indefrey, 2009b). Hilabeteetako ikastaro baten ondoren, egin zen datuen iturri berreraikitzeak, urraketa sintagmaren erantzunak ezker hemisferioko sare perisilbikoan anplitude handiagoa zutela erakutsi zuen. Efektu nagusia hizkuntza sarean kokatzeak, H2ko oroimen berriak dagoeneko lexikoa eta gramatika prozesatzen duten eremuetan sortu eta txertatzen direla adierazi lezake; eta ez beste prozesu kognitiboetaz arduratzen diren eremu baztertuetan.

Hala ere, nahiz eta hauek hizkuntzarekin lotutako burmuin eremuak izan, bloke

hauetan topatutako efektuak estatistikoki marjinalki esanguratsuak direla soilik eta, gainera, Gazteleran topatutako efektuen ezberdinak dira (gogoratu Gaztelerazko aurre-probak efektua bi hemisferioetan kokatzen duela). Posible da partaideek lehenengo blokean baino prozesu automatikoagoak erabiltzea ariketa gauzatzeko. Hala ere, erantzuna H1an izaten den erantzunaren ezberdina izanik (anplitudea handiagoa da gaztelerazko erantzunean), izan daiteke sorrarazitako erantzunaren anplitude ezberdintasunak gaitasun ezberdintasunak isladatzea.

Azkenik, bloketik blokeera topatutako ezberdintasunen azalpen posible bezala, MEG seinalearen aldakortasun intrinsikoa ezin da baztertu. Portaeran emandako emaitzak goi-mugan zeuden arren, urraketa efektua magnitude txikiagokoa eta laburragoa zen Euskaraz Gazteleraz baino. Diferentzia txikiak aldakortasun estatistiko handiarekin lotuak daude, beraz, bloketik blokeera topatutako ezberdintasunek efektuaren aldakortasuna isladatu dezakete.

Orokortze proba

Partaideek hiru trebakuntza blokeetan partaideek erakutsi zuten erantzun zuzenen maila orokortze proban mantendu zuten. Proba honetan erabilitako estimuluak izen eta adjektibo berriez (orain arte frogan azaldu gabeko) izen eta adjektiboez osatuta zeuden. Proba honen bitartean partaideek ez zuten beraien erantzunen zuzentasunaren inguruko informaziorik jaso. Beraz, badirudi partaideak trebakuntzan ikasitako araua sintagma berrietara orokortzeko gai izan zirela.

Bloke honen adierazle neuronalei dagokienez, denborari lotutako analisiak ERF efektuaren hasiera aurreko blokeen hasierekin bat egiten duela erakusten du. Efektuaren magnitudea bigarren eta hirugarren blokeetan eta Gaztelerazko aurre-proban topatutako efektu magnitudeen antzekoa da. Efektuaren topografia bi hemisferiotako sensore tenporaletan aurkitu zen, trebakuntzako hirugarren bloke eta Gaztelerazko aurre-proba blokeen antzera. Hala ere, iturri analisiek ez zuten efektu esanguratsurik azaldu. Datuen joerak efektua Gaztelerazko aurre-proban agertzen diren eremu batzuetan kokatuko luke efektua: ezker lobulo parietala (opercularis, arteka zentralaren aurre eta ondorengo zirkunboluzioak), lobulu tenporala (behe, erdi eta goi zirkunboluzioak) eta eskuin behe parietal eermua, supramarginala eta arteka zentralaren ondorengo zirkunboluzioa. Bloke honetako efektuak indar estatistikoki txikia duela eta, ezin da ondorio sendorik atera.

Bloke honetan bi neurgailuk (portaera eta sensore mailak) Gaztelerazko aurre-proban topatutako patroi antzekoak erakusten dituzte, manipulazio morfosintaktikoen erantzunak ikasketa prozesuaren hasieran ere H1en patroietara

moldata eta hitz berrietara orokortu daitezkeela adieraziz. Nahiz eta estatistikoki esanguratsuak ez izan, bi iturri analisiek H1-en antzerako patroia bat erakusten dute. Hala ere, Euskarazko efektua Gaztelerazkoa baino lehenago agertzen da. Paradigma mota hau ez da oso ikertua izan Euskarazko materialekin, beraz, zaila da aurreko ikerketetako denborekin konparatzea. Izan daiteke, berez, Euskarazko eta Gaztelerazko urraketa erantzunen denborak berdinak ez izatea. Ez dugu uste topatutako efektuak estimuluek eraginda direnik, Euskarazko aurre-proban ez bait zen egoeren arteko ezberdintasunik atzeman. Gainera, efektuaren hasiera denbora oso antzekoa da trebakuntza bloke eta orokortze probetan. Honek topatutako ezberdintasunak urraketa kontrol efektu bat direnaren segurtasuna ematen digu. Hala ere, ikerketa gehiago behar da ziurtatzeko ea iturri mailako efektu falta indar estatistikoaren eragina den edo efektua orokortze proban mantentzen ez delako den ulertzeko.

Gaztelerazko ondorengo proba

Portaera emaitzek partaideek proba ondo egin zutela erakusten dute, Gaztelerazko aurre-probaren emaitza antzekoak lortuz, espero zen bezala.

Espero ez bezala, ERF analisiek ezberdintasunak erakutsi zituzten Gaztelerazko aurre eta ondorengo proben artean. Ondorengo probako efektua nahiko beranduago hasi zen (580 ms puntu kritikoaren ondorean, 240 ms orde) eta soilik 150 ms iraun egin zituen (aurre-probako efektuak 360 ms iraun zituen). Gainera efektuaren magnitudea apalagoa zen eta topografia ezberdina. Ondorengo-probako efektua nagusiki eskuin sensore frontaletan kokatu zen, nahiz eta, ezker sensore tenporal gutxi batzuetan ageri zen ere. Denboran mugatutako iturri analisiak eskuin eremu frontaletan kokatzen du efektua, mugatu gabeko analisiak berriz, urraketa-kontrol efektua ezker parietal eremutan eta denbora leihoko ezberdin batean kokatzeko joera erakusten du.

Gaztelerazko aurre eta ondorengo proben arteko ezberdintasunentzat azalpen ezberdinak daude. Gaztelerazko ondorengo proba saioko azkenetako blokeetako bat zen eta partaideak nekatuta egon zitezkeen. Nahiz eta erantzun zuzena eman, erantzun hori lortzeko bidea ezberdina izan liteke. Beste azalpen posibleago bat, topatutako ezberdintasunak aldaketa efektu bat izatea liteke. Bigarren saioan partaideak trebakuntza eta orokortze proba egin zituzten Euskaraz. Beraz, partaideak Euskaraz ordubetez murgilduta egon ondoren, ariketa berdina inhibititu-berri zuten beraien H1an burutu behar zuten. Hala ere, esperimentu hau gramatika arau baten ikasketa prozesua aztertzeko diseinatua dago eta ez egoera konkretu honi erantzun bat emateko, beraz diseinuak ez gaitu baimentzen azalpen bat edo beste aukeratzen.

Aurrerantzean egingo diren ikerketetan, deskantsu baten ondoren bigarren Gaztelera bloke bat burutu beharko litzateke azalpen garbiago bat izateko.

Eztabaida orokorra

Portaera emaitza eta emaitza elektrofisiologikoetan oinarrituz, gramatika arau bat indibidualki erakutsia denean, trebakuntza intentsiboko paradigma batean, ikasketa prozesua azkar gertatu daitekeela aurkitu da (ordu batzuen baitan). Gainera, ikasketa hau aldaketa H1-ra gerturatzen diren neuronalez lagundua dago, aurreko ikerketetan erakutsi izan den bezala (Davidson and Indefrey, 2009a,b, 2011; Mueller et al., 2005, 2007, 2008). Hala ere, emaitza hauek, ikasleen eta ama-hiztunen burmuin erantzun berdinak topatzen dituzten beste ikerketa batzuekin kontraesanean daude (Pakulak and Neville, 2011; Meulman et al., 2014; Díaz et al., 2016). Emaitza ezberdin hauek azaltzeko aurkezten den hipotesia hurrengoa da: trebakuntza paradigmek ikasketa prozesu hasierako prozesuak jasotzen dituzte, eta hauek epe-luzeko paradigmek jasotzen dituzten dinamiken ezberdinak izan daitezke, Gainera, badaude ama-hiztunen eta ikasleak konparatu dituzten ikerketak non ikasle helduek ez zituzten ama-hiztunen patroik antzekoak erakutsi (Kotz et al., 2008). Morgan-Shorten arabera (Morgan-short et al., 2010) ama-hiztunen eta ikasleen arteko ezberdintasunak ez datoz soilik ikasleen adinak eraginda, beste faktore askoren interakzioen eraginez baizik, adibidez, adina, hizkuntza maila edo trebakuntza mota (ikus ere Caffarra et al., 2015). Osterhoutek beste interpretazio bat eman zien ezberdintasun mota hauei (Osterhout et al., 2006). Bere ustez, ezberdintasun hauek trantsizio fase bat isladatzen dute non ikasleek ez dira hizkuntza maila nahikora iritsi H1-en antzeko patroiak erakusteko. Tannerek diferentzia indibidualek H2 jabetzaren fasea isladatzen dutela proposatu zuen (Tanner et al., 2013).

Hemen aurkeztu den esperimientua ikasketa hasieran ematen diren burmuin aldaketak aztertzeko diseinatu zen, eta ez epe-ertain luzeko finkapena aztertzeko. Muga hau kontuan izanik, diseinu honek ez du baimentzen Euskarazko ikasleek epe luzean lortuko dituzten patroien ondorio sendo bat ateratzen, beraz ezta hauek Gaztelera dituzten patroien antzekoak izango diren edo ez aurreratzen. Hala ere, uste dugu garrantzitsua dela norabide honetan lan egitea ikasleen eta ama-hiztunen burmuin erantzunen arteko kontraesanak eta ezberdintasunak noiz eta zergatik azaltzen diren hobeto ulertzeko. Adibidez, Meulmanek Holandeseko ikasleek eta ama-hiztunek genero urraketen aurrean dituzten burmuin erantzunak ez direla antzekoak erakutsi zuen (Meulman et al., 2014). Diazen ustez horrelako ezberdintasunak hizkuntzen arteko distantziarekin lotuta daudela proposatu zuen (Díaz et al., 2016). Gaztelera ama hiztunak aztertu zituzten, batzuek Euskara

bizitzan goiz ikasi zuten beste batzuek beranduago. Subjektu-aditz konmuztadura (H1 eta H2an existitzen da) eta objektu-aditz konmuztadura (konmuztadura bietan existitzen da baina, konmuztadura zehatz hau soilik H2an) eta ergatibo konmuztadura (soilik H2an existitzen da) urraketak zituzten esaldiak erabili zituzten. Partaideen Euskara jabetze adin guztietan efektu bera topatu zen: soilik H2an existitzen zen hizkuntz ezaugarrian, burmuin erantzunak ama-hiztunen erantzunen ezberdinak ziren.

Nahiz eta lan honetan 'arau bakarreko gramatika ikasketa' aztertu den, lan honen aurkikuntza nagusia gramatika ikasketaren adierazle anatomikoak aurkeztzen dituela da. Hizkuntzaren azpi-sistema ezberdinak eremu kortikal ezberdinetan oinarritzen direla eta eremu bakoitzak bere plastikotasun profil ezberdina duela proposatu izan da (Sanders et al., 2008). Sintaxia eta fonologia heldutan ikasiak izateko arazo gehien aurkeztzen duten azpi-sistemak izateagatik ezagunak dira. Ikerketa batzuek fonologia ikasketaren iturri berreraikitzeak aurkeztu dituzten arren (laburpen baterako ikus Zhang and Wang, 2007), literaturan gramatika ikasketaren hasierako faseen adierazle anatomikoak ikertu dituzten lan gutxi aurkitu daitezke (Davidson and Indefrey, 2009b; Hultén et al., 2014).

Amaierako jabetza oraindik eztabaidatua den arren, azken ikerketek ama-hiztunen eta denbora epe luze batez hizkuntzarekin harremanetan egon diren ez-ama-hiztunen arteko konparaketetan zentratu dira (Meulman et al., 2015; Hanna et al., 2016; Sung et al., 2016; Díaz et al., 2016; Johnson et al., 2016). Hala ere, horietako gutxik erabili dute iturri berreraikitzea ahalmentzen zuen teknikaren bat (Hanna et al., 2016). Hemen aurkeztutako lanak, gramatika ikasketa bitartean burmuinaren dinamikak definitzea eta partaidearen H1 eta H2 erantzunak deskribatzea posible dela erakusten du.

Trebakuntza blokeak aztertzean, azkeneko bietan patroia amankomuna topatu daiteke: kontrol eta urraketa egoerek sorrarazitako aktibitatea ezker hemisferioan topatu zen, zehazki ezker lobulu tenporalean (behe, erdi eta goi zirkunboluzioetan), parietal lobuluan (supramarginala, arteka zentralaren aurre eta ondorengo zirkunboluzioetan), ezker zirkunboluzio angularrean, nahiz eta hau ez zen lehengo blokearen kasua (aurrerago azaltzen da). Ez daude heldutan emandako gramatika ikasketaren inguruan MEG teknikarekin egindako ikerketa asko. Holandesa ikasten zuten alemaniarrek sintagma-ordenaren urraketari sorrarazitako MEG erantzunak aztertu zituen Davidson and Indefrey (2009b)-ek. Bertan egindako iturri berreraikitzeak hilabeteetako ikastaro baten ondoren ezker hemisferioko sare periselbikoak (behe frontal eta ezker lobulu tenporala) erantzun anplitude handiagoa erakutsi zuen urratze egoeran. Honetaz gain, (Hultén et al., 2014)-ek ama-hizkuntza Finlandesa zuten partaideak objektu konmuztadura lantzen zuen

hizkuntza miniaturizatu artifizial batean trebatu zituen. Lau eguneko trebakuntzaren ondoren, partaideak mintzamen ariketa bat egin behar zuten MEG seinaleak grabatu bitartean. Konmuztadurak sorrarazitako erantzunaren indarra modulatu zuen ezker goi kortex tenporalean eta eskuin okzipito-tenporalean. Orain deskribatutako patroia amankomunetaz gain, tesi honetako esperimentu honetan trebakuntza bitarteko aldaketak topatu zirenera, hau da, bloke bakoiztean eremu ezberdinetako aktibitatea nagusitu zen.

Lehenengo trebakuntza blokean topatutako sorrarazitako aktibitatearen patroiak, beste Euskarazko blokeetan topatutako patroien oso ezberdinak dira. Azken blokeetako patroiek Gaztelaniazko (H1) patroiak gogorarazten dute. Zehatzago, lehenengo trebakuntza blokeko iturri berreraikitzeak sorrarazitako aktibitatea ezker sare periselbikoan kokatzen du bai urraketa bai kontrol egoeratan. Hala ere, hurrengo Euskarazko blokeetan ezker sare periselbikoko sorrarazitako aktibitate altuagoa soilik urraketa egoeratan topatu zen. Nahiz eta hau topatutako patroia orokorra izan, analisi estatistikoek ez dute patroia osoa sostengatzen, burmuin eremu batzuk soilik. Sarreran aipatu den bezala, lan hau ikerketa esploratorioa da. H2 ikasketako prozesuko hasierako faseak ikertu gabe daudenez, zaila da aurreikusten zein burmuin eremurik izango duten garrantzia prozesu hauetan eta ezin dugu analisia eremu konkretu batzuetara mugatu. Ahal dela, lan honetan topatutako adierazle anatomikoak hurrengo ikerketetan hipotesi zehatzago bat eraikitzen lagunduko dute eta beraz, berrespen analisi klasikoagoak egiteko aukera izango da.

Davidson and Indefrey (2009b) lanean, sare periselbikoaren barruan efektuaren kokalekua aldakorra zen MEG saioaren arabera (Holandes ikastaro baten bi aste edo hiru hilabete pasa ondoren). Hasierako saioetan efektua ezker goi eremu tenporaletan kokatu zen, hemen aurkeztutako erantzunen antzera. Trebakuntzako lehenengo blokeak, urraketa egoeran kontrol egoeran baino sorrarazitako aktibitate handiagoa erakusten du eskuin zirkunboluzio supramarginalean, baino beste blokeetan eremu honetako aktibitatea ez du egoerak modulatu. Indefrey (2006)-ek H2 prozesamenduaren inguruan egin zuen fMRI ikerketen laburpenaren arabera, ariketa burutzeko esfortzua faktore bat izan daiteke. Adibidez, hasierako Euskarazko blokeen eta Gaztelaniazko blokearen arteko ezberdintasunak ariketa egiteko behar den esfortzuaren isla izan daitezke, eta trebakuntza ondorengo H1 eta H2ren arteko antzekotasunak partaideek ariketa modu efektiboago batean egiten ikasi dutenaren isla izan daiteke. Indefrey (2006)-ek H1 eta H2 prozesamendu sintaktiko bitartean topatzen diren BOLD seinaleen ezberdintasunak deskribatu zituen, bereziki erabaki metalinguistiko bat behar dituzten ariketak. Morfema inflekzioa aztertzen zuten ikerketek trebakuntza izan ondoren (2 hilabete), ezker atzealdeko IFG eremuan, H2 morfemari erantzunez, trebakuntza aurretik baino

aktibazio altuagoa erakusten zuen eta eremu hau H1 prozesatzeko eremuarekin koinziditzen du. Ikerketa bera trebakuntza luzeago bat (6 urte) izan zuten partaideengan burutzerakoan eremu honetako BOLD seinalea ahulagoa zela topatu zuten. Indefreyren arabera eremu batek ariketa linguistiko batean parte hartzen duenean, hasieran aktibitate neuronal altuagoa erakusteak ariketa honetan jarritako esfortzua isladatzen du. Trebakuntza urteen ondoren aktibitate ahulagoak ariketa modu efektiboago batean prozesatzen dela isladatu dezake. Modu antzeko batean, tonu eta fonetika ikasketa ikerketa laburpen batek (Zhang and Wang, 2007), gaitasunean topatzen diren hobekuntzak ezker hizkuntza sarearen BOLD seinale handiago batekin lotuta daudela erakutsi zen. Bestalde, epe-luzeko ikasketaren ondoren, ikasleek BOLD seinale ahulagoa erakusten zuten. Egileen arabera, patroï aldaketa hauek ikasketarekin adierazpen kortikalak aldatu daitezkeela adierazten dute.

Ondorioz, lehenengo trebakuntza bloketik hurrengo blokeetara sorrarazitako aktibitatearen iturri berreraikitzean topatutako aldaketek Indefrey (2006) eta Zhang and Wang (2007) lanek azaldutako aldaketa progresiboak isladatu ditzakete. Hala ere, lehenago azaldu bezala, bloketik blokerara agertzen diren ezberdintasunak azaltzeko ezin da aldakortasun intrinsikoa baztertu (ikus 3.4 atala). Lan honen helburua aldakortasun honen deskribapen bat ematea da, aurrerago egiten diren ikerketek patroï hauek gramatika arau eta hizkuntza konbinazio ezberdinetan sendoak diren edo ez aztertu dezaten.

Azkenik, esperimentu honetako materialak gramatika zati txiki batez osatuak daude, eta Mueller et al. (2007)-en azaldu bezala ariketa honetako portaera emaitzak goi-mugan egoteak ez du esan nahi 'H2 osatu' batean ama-hiztunak bezala arituko liratekeenik. Arau baten ikasketak (beste arau batzuekin nahasita ikasten denean edo hizkuntzaren beste aspektu batzuekin ikasten denean), ea patroï antzekoak erakusten dituen edo ez aztertu behar da.

3.5 Laburpena

Portaera emaitzek H2 ikasle helduek maila altuak lortu ditzaketela erakusten dute, gutxienez hizkuntza zati txikietan eta gramatika arau sinpleekin. Hala ere, hau hizkuntza miniaturizatu bat da, eta ariketa honetako emaitzak jomugan egoteak ez du H2 hizkuntzan ama-hiztun baten maila adierazten. Lan gehiago behar da ikasleek H2 'osatu' bateko sintaxia nola prozesatzen duten ulertzeko. Honetaz gain, trebakuntza ordu batzuen ondoren H2 prozesamenduan ematen diren erantzun elektrofisiologikoak H1 erantzunen antzekoak direla erakutsi da.

Laburbilduz, trebakuntza epe-motze baten ondoren H2 prozesamenduan aldaketak topatu daitezkeela erakutsi da, eta ondorioz, H2 ikasketa modeloek aldaketa azkar hauek kontuan hartu beharko lituzkete.

4. Kapitulu

Esaldien ulermen esperimentua

4.1 Oinarrizko arrazoia

Kapitulu honek oszilazio kortikalek hizkuntza ikasketan duten eginkizuna aztertzen du, ikasi-berri den hizkuntza bat eta ama-hizkuntza konparatuz. Irakurketarekin alderatuz, gutxi dakigu bigarren hizkuntza bat entzutean gertatzen diren oszilazioetat. Hizkuntza ikasketak eragindako aldaketa oszilatarioak aztertu ziren. Estimulu luzeak erabili ziren, theta (4-8 Hz), alpha (8-13 Hz) eta beta (13-30 Hz) frekuentzia bandetan gertatutako aldaketak irudikatu ahal izateko. Lan honek ama-hizkuntza ingelesa duten eta gaztelaniazko jakintzarik ez zuten partaideetan, Gaztelerazko trebakuntza ordu gutxi batzuen aurretik eta ondoren, MEG erabiliz neurtutako aktibitate induzituaren iturri berreraikitzeak aurkezten ditu.

4.2 Metodo eta Materialak

Adierazpen etikoa

Ikerketa hau Sir Peter Mansfield Imaging Centre-n egingo da eta bertako etika komiteak onartua da. Partaide guztiek idatzizko kontsentimendua eman zuten (Declaration of Helsinki) esperimentua hasi aurretik.

Partaideak

Partaideak irakurketa eta entzumen arazorik ez zuten 18 (6 emakume, 12 gizon) gaztelerazko jakintzarik gabeko ingelesezko ama-hiztun osasuntsu eta eskuinak izan ziren. Oartaideak Peter Mansfield Imaging Centre (University of Nottingham)-en bilatutakoak ziren. Esperimentua hasi aurretik, partaide guztiak interferentzia magnetikoen bila miatuak izan ziren. Bi partaide gehiagoren datuak jaso ziren, baina

analisitik baztertuak izan ziren batek gehiegizko artefakto magentikoak aurkezten zituelako eta bestea trebakuntzaren helburua lortu ez zuelako.

Estimuluak

Hochmuth et al. (2012)-ren lana oinarri hartuta, matrize esaldiak erabili ziren, hiztegi kopuru txiki bat erabiliz esaldi asko eraikitzeke aukera ematen dutelarik. Esaldi bakoitza subjektu (berezko izen bat) eta beste lau hitzez osatua zegoen: aditza, zenbakia, objektua eta adjektibo bat. Hitz kategoria bakoitzak 5 hitz zituen, ondorioz, semantikoki eta gramatikoki zuzenak ziren 625 esaldi berdingabeak eraiki ahal izan ziren ingelesezko eta gaztelerazko egoerentzat ($5 \times 5 \times 5 \times 5 = 625$). Matrize esaldiak erabiliz, hitzak ulergarriak izan arren ezin dira aurreikusitakoak. Honek esan nahi du, esaldi osoa ulertzeko esaldi horretako hitz guztiak ulertu behar direla: trebakuntza saioen ezinezkoa da esaldi osoak memorizatzea.

Beste hiztegi multzo bat erabiliz, ingelesezko beste matrize esaldi sorta bat eraiki zen. Bi esaldi sorta ezberdinak itzulpen efektuak ekiditeko erabili ziren, esperimentuaren diseinu atalean sakonago azaltzen da hau.

Estimuluak soinu-kabina batean Ingelerazko eta Gaztelerazko ama-hiztunak ziren bi emakumek grabatu zituzten. Audioen anplitudea bolumen berdineran ekualizatu zen eta 55 dB-tara aurkeztu ziren, Promold aurikularrak (International Aquatics Trades, Santa Cruz, CA) and EARTONE 3A Insert Earphone transducers (EAR Auditory Systems) erabiliz.

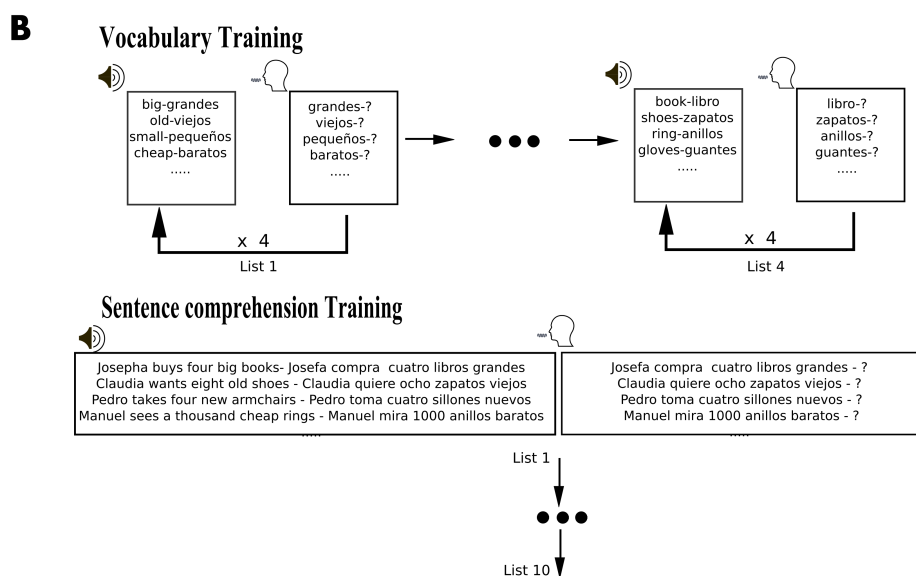
Diseinua eta ariketak

Esperimentua bi egun jarraietan egindako bi saiotan banatuta dago (4.1. irudiak diseinua laburtzen du). Bi eguneko diseinua aukeratzeko bi arrazoi nagusi zeuden. Lehenengoa, trebakuntza fasean jabetutako jakintzaren finkatzea ahalbidetzeko. Bigarrena, partaideek jakintza maila altua lortzeko entsaio kopuru altua behar zelako. Lehenengo saioa (ikus 4.1 irudia, A panela ezkerreko zutabea) 5 blokez osatua dago: hasierako atsedeen blokea, jarraian ingelesezko esaldien entzumena, ondoren gaztelerazko esaldien entzumena, gaztelerazko ulermen-proba bat eta azkenik trebakuntza saioa Gazteleraz. Bigarren saioak (ikus 4.1 irudia, A panela eskuineko zutabea) 4 blokez osatua dago: hasierako atsedeen blokea, jarraian ingelesezko esaldien entzumena, ondoren gaztelerazko esaldien entzumena, gaztelerazko ulermen-proba bat. Hurrengo puntuetan bloke bakoitza zehatzago deskribatzen da.

A

	DAY 1	DAY 2
	Resting State 10 min	Resting State 10 min
	English Listening ~10 min	English Listening ~10 min
	Spanish Listening ~10 min	Spanish Listening ~10 min
	Spanish Test ~20 min	Spanish Test ~20 min
	Spanish Training ~2 h	

MEG blocks
 Behavioural blocks



4.1. irudia: Ikerketaren diseinua. A panelak burututako ariketak zerrendatzen ditu. Ezkerreko zutabeak lehenengo saioan egindako ariketak azaltzen ditu, eta eskuineko zutabeak bigarren saioan egindakoak. Gris ilunean markatutako ariketak MEG grabaketak dituztenak dira. Gris argiz markatutako ariketak portaera ariketak dira. B panelak trebakuntza saioaren detailak aurkezten ditu.

Atsedeen blokea (MEG): Atsedeen egoerako datuak bildu ziren 10 minutuz. Partaideei lasai egon eta begirada atzealde gris batean agertzen zen gurutze txuri batean finkatzeko eskatu zitzaien.

Esaldiak entzuteko proba (MEG): 10 s ko isiltasunaren ondoren, esaldiak launakako taldetan aurkezten ziren (10 s). Bloke bakoitzak 30 entsaio zuten (120 esaldi) eta gutxi gorabehera 10 minutuko iraupena zuen. Saio bakoitzeko, bloke bat Ingeleraz eta beste bat Gazteleraz burutu ziren. ingelesezko lehenengo saioan lehenengo hiztegi multzoko matrize esaldiak erabili ziren, eta bigarren saioan bigarren hiztegi multzoko matrize esaldiak erabili ziren. Bigarren saioan hiztegi multzo ezberdina erabiltzeko arrazoia, behin partaideak trebatuta daudela ingelesetik gaztelerara edozein itzulpen saiakera ekiditeko da, eta Ingelerazko entzutezko garbia jasotzea. Bigarren hizkuntzatik ama-hizkuntzara aldatzeak sortzen duen koste altua ekiditeko (Costa and Santesteban, 2004), beti ingelesezko blokea Gaztelerazko blokearen aurretik aurkeztu zen.

Gaztelerazko ulermen proba (Portaera): Ariketa honetan partaideek banan-banan gaztelerazko 25 esaldi entzun eta hauen ingelesezko itzulpena idatzi zuten. Esaldi bakoitza itzuli aurretik, esaldi hori soilik behin entzuteko aukera izan zuten.

Gaztelerazko trebakuntza (Portaera): Trebakuntza lehenengo saioko MEG grabaketa eta gaztelaniazko ulermen probaren ondoren burutu zen. Trebakuntza saio bakoitza 1.5 - 2 ordu artean iraun zituen. Trebakuntza saioaren egitura Hultenen lanean oinarrituta dago (Hultén et al., 2014), lehenbizi hiztegia sortzen da eta ondoren esaldi osoen ulermenean trebatzen dira partaideak. Horregatik trebakuntza saioa bi blokeetan banatu zen: hiztegi ikasketa eta esaldien ulermena (ikus 4.1 irudia, B panela):

1) Hiztegi ikasketa: Bozgoragailuetatik bost ingelesa-gaztelera hitz bikote (e.g. 'Big - Grandes') aurkeztu ziren. Ondoren, Gaztelerazko hitz berdinak banan banan aurkeztu ziren eta partaideek honen ingelesezko itzulpena esan behar zuten. Une oro emandako erantzunaren inguruko informazioa helarazi zitzaien partaideei. Bi sekuentzia hauek lau aldiz errepikatu ziren hitz bikote multzo bakoitzeko. Prozedura hau gaztelera-ingelesa hitz bikote guztiak aurkeztuak izan ziren arte errepikatu zen (ikus 4.1 irudia, B panela).

2) Esaldien ulermena: Esaldien ulermenenean trebatzeko, hiztegi ikasketaren egitura berdina erabili zen. Bozgoragailuetatik bost ingelesa-gaztelera esaldi bikote aurkeztu ziren. Ondoren, gaztelerazko esaldiak banan banan aurkeztu ziren eta partaideak honen ingelerazko itzulpena esan behar zuen. Une oro emandako

erantzunaren inguruko informazioa helarazi zitzaion partaideari: bai ea itzulpena zuzena edo okerra zen eta gogoratzen ez zituen hitzen itzulpena errazten zitzaion. Esaldi osoa guztiz ondo itzuli arte ez zen beste esaldirik aurkezten. Partaideek bost esaldiz osatutako zortzi bloke burutu zituzten (ikus 4.1 irudia, B panela).

Prozedura

Partaide bakoitzarentzat deskribatutako bloke guztiak grabatu ziren. Grabaketa bitartean partaideei, postura eroso hartu eta erlaxatzeko eskatu zitzaien datu grabaketa bitartean mugimenduak ekiditeko asmoz. Ariketen bitartean begi, buru eta gorputz mugimenduak saihesteko eskatu zitzaien.

MEG datuak partaideak etzanda zeudela, 275 kanaleko CTF MEG (MISL, Coquitlam, Canada) ekipamendu baten berezko softwarean bidez, 600 Hz lagintze-abiadura eta hirugarren gradiometro sistema martxan zela jaso ziren. Grabaketaren aurretik hiru lokalizazio espira kokatu ziren partaide bakoitzaren fiduzialetan.

Buruaren forma (400 puntu inguru) eta hiru fiduzialak digitalizatzeko Polhemus Isotrak (Polhemus, Colchester, VM, EEBB) boligrafo bat erabili zen, burua MEG sensore arrayra koregistratu ahal izateko. Partaideen anatomia bolumetrikoko MR irudiak, 3T MR system (Phillips Achieva, Best, Netherlands) ekipamendua eta MPRAGE sekuentzia erabiliz jaso ziren (1 mm³ zehaztapena). Datu bilketaren ondoren, buruaren gainazala atera eta *surface matching* teknika erabiliz bloigrafoak jasotako buruaren formarekin koregistratu zen. Honek, MEG sensore arrayaren eta burmuinaren anatomiaren koregistratio osoa ahalbidetzen du, alderantzizko eta joanerazko modeloen kalkuluak erraztuz.

Analisiak

Portaera analisiak

Ulermen probak puntuatzeko garaian, zuzenki itzultako hitz bakoitzeko (berezko izenak kontatu gabe) puntu bana jasozten zuten partaideek. Partaideen atalean azaldu bezala, partaide bat baztertua izan zen bere itzulpen zuzenen kopurua ez zelako % 50-ra iristen.

MEG datuak

CTF MEG (MISL; Coquitlam, BC, Canada) ekipamenduak dakarren DataEditor softwarea erabiliz, bildutako MEG datuak 1 eta 150 Hz arteko banda-pasa batekin

iragazki ziren. Linea elektrikoaren frekuentzia (50 Hz) eta honen harmonikoak iragazki ziren ere. Ondoren, artefaktuak antzemateko datuak bisualki miatu ziren. Artefaktu gehiegi edota 5 mm baino gehiagoko buru mugimendua zuten entsaioak baztertu egin ziren. Zehazki, magnetomiograma, magnetokardiograma eta magnetookulograma baten ezaugarriak zituzten entsaioak baztertu ziren. Partaideen atalean azaldu den bezala, partaide bat baztertua izan zen gehiegizko interferentzia magnetikoak erakutsi zituelako. 4.1 taulak, bloke bakoitzean MEG analisisetan erabilitako batezbesteko entsaio kopuruak aurkezten ditu.

	1. Saioa	2. Saioa
Ingelera	26.22 (2.46)	27.33 (3.25)
Gaztelera	26.61 (2.72)	27.5 (3.07)

4.1. taula: MEG analisisetan erabilitako batezbesteko (std) entsaio kopuruak.

Iturri analisia

Aurre-prozesamenduaren ondoren, beamformer iragazki espaziala erabili zen (Van Veen et al., 1997). Horretarako, datuen kobariantza matrizea kalkulatu zen 1-150 Hz frekuentzia leihoa eta esperimendu osoa biltzen duen denbora leihoa erabiliz. Erregularizazioa burutzeko Tikhonov metodoa aplikatu zen, erregularizatu gabeko matrizearen balio propio maximoaren % 5ko parametroa erabiliz. Boxelak burmuin osoa estaltzen zuen 4mm-ko lauki-sare erregular (spatial grid) baten barruan definitu ziren eta joanerako modeloa esfera-lokal-anitzeko metodoa erabiliz kalkulatu zen (Huang et al., 1999). Boxel bakoitzean banda zabaleko seinaleko (1-150 Hz) beamformer iragazkiak kalkulatu ziren. Ondoren, sensore mailako datuak hiru bandatan iragazki ziren: theta (4-8 Hz), alpha (8-13 Hz) eta beta (13-30 Hz). Frekuentzia banda bakoitzeko kobariantza matrizea kalkulatu zen esperimendu osoa biltzen duen denbora leihoak erabiliz. Jarraian, frekuentzia banda bakoitza frekuentzia zabaleko (1-150 Hz) iragazkiak erabiliz iragazi ziren, frekuentzia banda bakoitzeko iturri mailako mapa bat lortuz. Iturri mapak kontrol leiho (Pk) eta leiho aktiboen (Pa) arteko potentzia aldaketa erlatiboa irudikatzen dute: $(Pa-Pk)/Pk$. Frekuentzia banda bakoitzeko potentzia aldaketa nagusiak identifikatzeko, frekuentzia banda bakoitzean All>Null eta Null>All kontrasteak kalkulatu ziren eta hauek $q < 0.05$ (FDR zuzenduak) ataria erbiliz mugatu egin ziren, estatistikoki esanguratsuak diren patroiak identifikatuz.

Bi analisi estatistiko ezberdin erabili ziren: Burmuin osoko analisia eta ROI analisia. Lehenengoak datuen inguruko inferentziak egiten ahalbidetzen du. ROI

analisian, frekuentzia banda bakoitzeko kontraste bat definitu zen estatistikoki esanguratsuak ziren eremuak bilatzeko. Jarraian, eremu hauetan egoeren arteko ezberdintasunak aztertu ziren. Eremu hauek burmuin osoko analisi baten eremu estatistikoki esanguratsuak izanik, egoeren arteko probek estatistikoki esanguratsuak izateko joera erakutsi dezakete. Hala ere, analisi mota hau hurrengo ikerketetan oinarriak ezartzeko baliagarria izan daiteke.

Burmuin osoko analisia

Frekuentzia banda bakoitzeko, burmuin osoko 2 (Hizkuntza: Ingerela/Gaztelera) bider 2 (Saioa: 1. eguna/2.eguna) ANOVAk kalkulatu ziren. Ondoren $q < 0.01$ (FDR zuzenduak) ataria erabiliz ANOVA hauen emaitzak mugatu ziren, estatistikoki efektu esanguratsua zuten eremuak identifikatzeko. Faktore esanguratsuetan, atari estatistikoa biziraundako burmuin eremuetan post-hoc analisiak burutu ziren.

ROI analisia

Interesezko eremuak definitzeko, frekuentzia banda bakoitzean burmuin osoko All>Null eta Null>All kontrasteetan ($q < 0.05$, FDR zuzenduak) ataria erabili zen. Frekuentzia banda bakoitzean definitutako eremu bakoitzean frekuentzia horren batezbesteko potentzia kalkulatu zen eta hauek 2 (Hizkuntza: ingelesa/gaztelera) bider 2 (Saioa: 1. eguna/2.eguna) ANOVAen bitartez aztertu ziren.

4.3 Emaitzak

Portaera analisia

4.2 taulak egun bakoitzean ulermen testean zuzenki itzultako hitz kopuruen batezbestekoak (std) erakusten ditu. Lehenengo egunean partaideek hitz gutxi itzuli zituzten zuzenki, bigarren egunean ordea, zuzenki itzultako hitz kopuruak nabariki gora egin zuen.

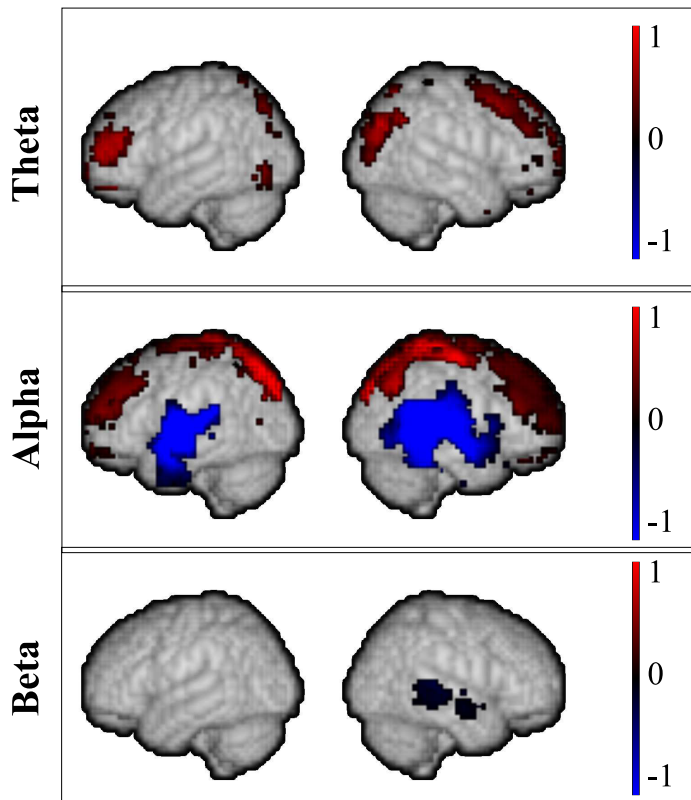
	1. Saioa	2. Saioa
Gaztelera	7.94 (6.6728)	81.46 (10.85)

4.2. taula: Zuzenki itzultako hitz kopuruen batezbestekoak (std).

Whole brain contrast

All > Null, Null > All

$q < 0.05$, FDR corrected



4.2. irudia: All>Null (gorria) eta Null>All (urdina) kontrasteak estatistikoki esanguratsuak diren burmuin eremuak ($q < 0.05$, FDR-zuzenduak).

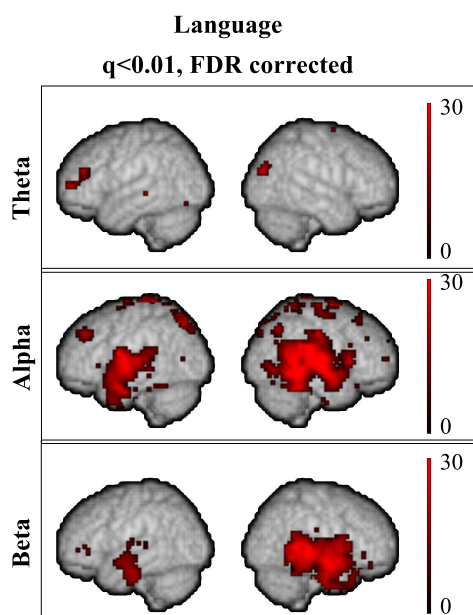
MEG datuak

Iturri analisia

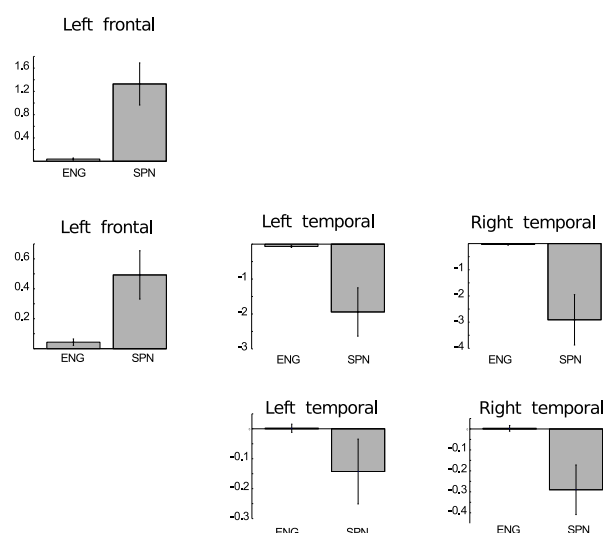
Burmuin osoko analisia

4.2 irudiak, frekuentzia banda bakoitzean, All>Null eta Null>All kontrasteak ($q < 0.05$, FDR zuzenduak) erabiliz identifikatutako potentzia aldaketak erakusten ditu. All>Null kontrasteak, theta bandan bi hemisferioetako eremu okzipital, frontal eta parietaletan eta alpha bandan eremu dorsaletan erakusten ditu potentzia aldaketak. Kontrako kontrasteak, Null>All, alpha bandan bi hemisferioetako eremu tenporaletan eta behe-parietaletan eta beta bandan eskuin erdi-lobulu tenporalean erakusten ditu potentzia aldaketak.

A Whole brain ANOVA



B



4.3. irudia: Burmuin osoko 2x2 ANOVAREN emaitzak. A panelak Hizkuntza faktorearen F mapak ($q < 0.01$, FDR-zuzenduak) erakusten ditu. B panelak A paneleko eremu nagusienetan egindako post-hoc analisiak.

Burmuin osoko ANOVA-ek ($q < 0.01$, FDR zuzenduak) estatistikoki esanguratsuak diren burmuin eremuak soilik Hizkuntza faktore nagusiarentzat topatu zituzten. Theta frekuentzia bandan, hizkuntzak eragindako burmuin aktibitate diferentziak ezker kortex aurre-frontalean aurkitu ziren. Alpha eta beta frekuentzia bandetan, bi hemisferioetako lobulu tenporaletan (ikus 4.3 irudia, A panela). Saioa faktore nagusiarentzat eta Hizkuntza eta Saioa interakzioarentzat ez zen estatistikoki esanguratsua den burmuin eremurik topatu.

Post-hoc analisiak (ikus 4.3 irudia, B panela) ezker kortex aurre-frontalean theta eta alpha potentzia altuagoa erakusten dute gazteleran ingelesean baino ($t = -3.67$; $p < 0.001$ thetan eta $t = -3.01$; $p < 0.001$ alphan). Gaztelerazko blokea ingelesezko blokearekin alderatzean, gaztelerazko blokeetan alpha potentziaren jaitsiera handiagoa topatu zen ezker eta eskuin lobulu tenporaletan, ($t > 2.78$; $p < 0.001$). Beta potentziaren jaitsiera handiagoa topatu zen eskuin lobulu tenporalen Gaztelerazko blokean Ingelerako blokearekin alderatuz ($t = 2.66$; $p = 0.008$). Ezker hemisferioan antzeko joera bat topatu zen ($t = 1.45$; $p = 0.08$).

ROI analisia

Intereseko eremuetan egindako ANOVA-en emaitzak erakusten ditu 4.4. irudiak.

Aurkikuntza orokor bezala, eremu guztiek Hizkuntzaren efektu nagusia erakutsi zuten ($F > 8.86$; $p < 0.004$).

Theta bandaren potentziari dagokionez, bai eremu okzipitalek, bai eremu frontalek theta sinkronizazio indartsuagoa erakutsi zuten Gaztelerazko blokeetan ingelesezko blokeetan baino ($F = 8.86$; $p = 0.004$ eremu okzipitalean eta $F = 11.13$; $p = 0.0014$ eremu frontalean). Bestalde, bi hemisferioetako eremu frontalek eta eskuin lobulu parietalak Saioaren efektu nagusia erakutsi zuten ($F = 6.62$; $p = 0.0123$); baita Saioa eta Hizkuntzaren arteko interakzio bat ere ($F = 6.72$; $p = 0.0113$).

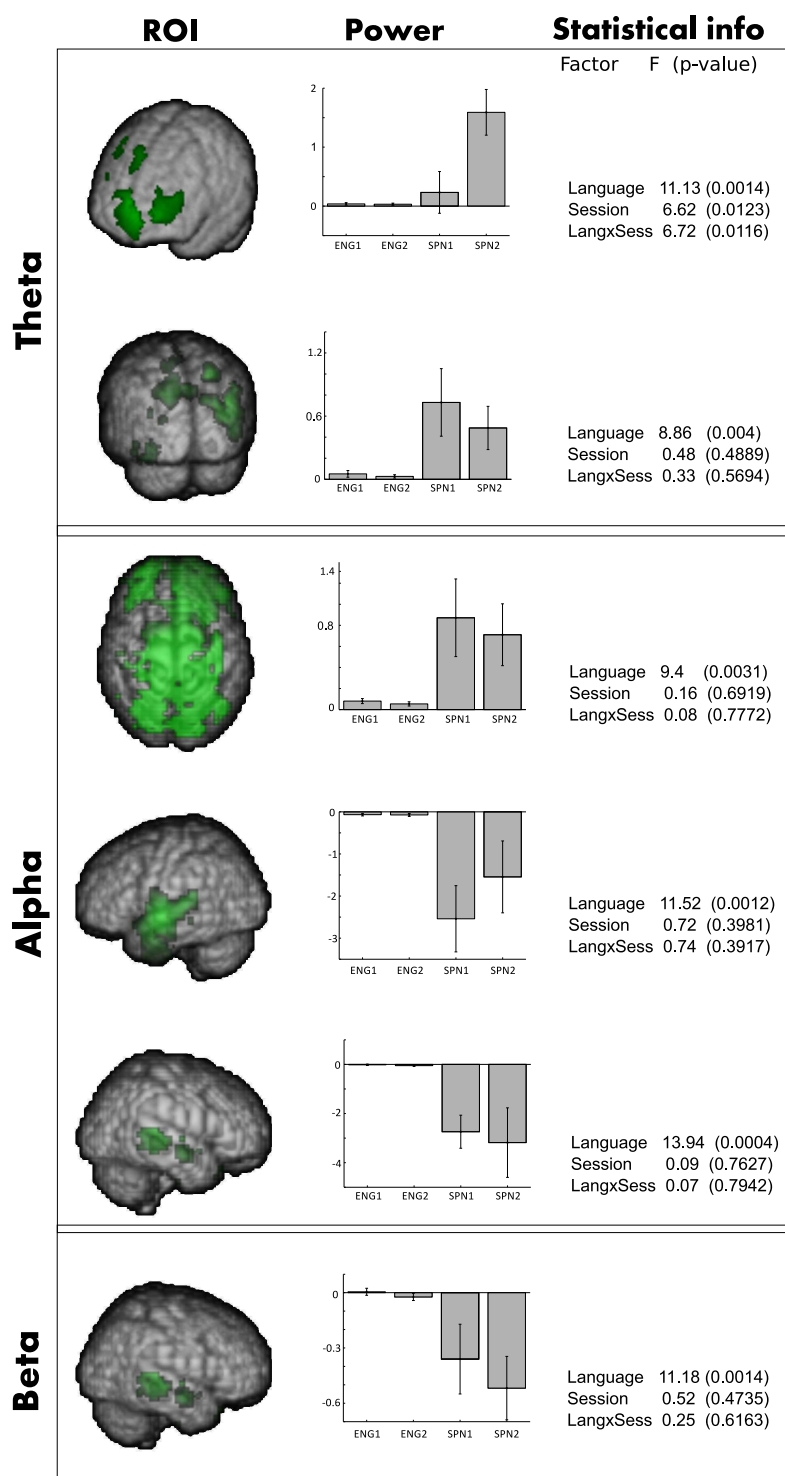
Alpha bandaren potentziari dagokionez, eremu dorsaletan alpha sinkronizazio indartsuagoa topatu zen gaztelerazko blokeetan ingelesezko blokeetan baino ($F = 9.4$; $p = 0.0031$). Bestalde, bi hemisferioetako lobulu tenporaletan alpha desinkronizazio handiagoa topatu zen gaztelerako blokeetan ingelesezko blokeetan baino ($F = 11.52$; $p = 0.0012$ ezker hemisferioan eta $F = 13.94$; $p = 0.0004$ eskuin hemisferioan). Post-hoc analisiek alpha desinkronizazio patroietan joera estatistiko bat erakusten dute: ezker lobulu tenporalean eta behe-parietalean gaztelerazko bigarren saioko desinkronizazioa lehenengo saiokoa baino txikiagoa (eta ingelesezko blokeen antzekoagoa) da ($t = -1.36$; $p = 0.09$). Eskuin lobulu tenporalean ez zen horrelako joera estatistikorik topatu ($t = 0.2463$; $p = 0.37$).

Beta bandaren potentziari dagokionez, Gaztelerazko blokeetan ingelesezko blokeetan baino desinkronizazio handiagoa zen ($F = 11.18$; $p = 0.014$).

4.4 Eztabaida

Esperimentu honen helburua epe-motzeko hizkuntza ikasketak aktibitate oszilatario kortikalean duen eragina aztertzea zen. Iturri berreraikitze teknikak hiru frekuentzia banden erantzun espaziala aztertzeko erabili ziren: theta (4-8 Hz), alpha (8-13 Hz) eta beta (13-30 Hz). Burmuin osoko analisiak kontrol leiho eta leiho aktiboen arteko potentzia diferentziak zehaztu zituen, mintzamenaren ulermenean frekuentzia bandek erakusten dituzten patroio orokorrak eskainiz.

Burmuin osoko analisiak theta eta alpha banden potentziak leiho aktiboan, erreferentzia basean baino altuagoak ziren eremu frontal eta okzipitaletan. Bestalde alpha bandako potentzia txikitu egin zen ezkerreko eta eskuineko lobulu tenporal eta behe-parietaletan. Beta bandaren potentzia txikitu egin zen eskuin lobulu tenporalean. Banda ezberdinek erakusten dituzten potentzia igoera eta jaitsierak literaturan topatutakoekin bat egiten dute, nahiz eta literaturako ikerketek potentzia



4.4. irudia: ROI analisi esploratorioa. Lehenengo zutabeak frekuentzia banda azaltzen du, bigarrenak aztertutako intereseko eremua (ROI), hirugarren zutabeak lau eremuetan eremu horren potentzia azaltzen du eta azken zutabeak ANOVaren emaitzak erakusten ditu.

aldaketa hauen kokalekuetan ez dute adostasunik erakusten (ikus Bastiaansen and Hagoort, 2006, laburpena).

Bi analisietan, eskuin lobulu tenporaleko alpha eta beta potentzia jaitsierak patroï antzekoak erakusten dituzte, bi jaitsiera hauek banda zabaleko efektu bat izan daitezkeela adieraziz.

Theta banda

Theta bandan, erreferentzia basearekiko potentzia igoera aurkitu egin zen bi hemisferioetako eremu frontaletan eta okzipitaletan eta eskuin parietalean. Burmuin osoko ANOVA analisiak ezker kortex frontalean theta sinkronizazioa gazteleraz ingelesez baino indartsuago zela erakutsi zuen. Hizkuntza ulermena aztertu duten aurretiko ikerketek theta sinkronizazioa lexiko berreskuratzearekin lotu izan dute (Lam et al., 2016; Bastiaansen et al., 2008, 2005). Hau oinarri bezala hartuta, aurkitutako theta sinkronizazio ezberdinak lexiko berreskuratzean egon daitezken ezberdintasunak adierazi ditzakete. Bi hemisferioetako eremu frontalean eta okzipitalletan eta eskuin parietalean aurkitutako modulazioak Lam eta lagunek topatutako patroïaren oso antzekoak dira (Lam et al., 2016). Ikerketa honetan, esaldian berandu agertzen diren hitzek, esaldian goiz agertzen diren hitzek baino theta sinkronizazio altuagoa erakutsi zuten eremu hauetan. Patroï honek ariketa kognitiboen eskakizunekin lotutako sare fronto-parietala gogorarazten du eta hori dela eta, lan horren egileek esaldian berandu agertzen diren hitzek eskakizun handiagoa behar izan dezaketela argudiatzen dute, memorian informazio gehiago mantendu behar delako. Hala ere, hemen aurkeztutako esperimentuan partaideek ez zituzten soilik hitzak memorian mantendu behar, baita mintzamenetik segmentatu ere (hitz antzematea eta mintzamen segmentazioa). Izan daiteke hitz antzematea eta mintzamen segmentazioa elkarri lotuta egotea. Ariketa bat ama-hizkuntzan burutzen denean informazio lexiko-semantikoak entzuleak segmentazio lanetan laguntzen ditu (Sanders and Neville, 2000). Gainera, bigarren hizkuntza batean pista lexikoak erabilgarri daude ere (Sanders et al., 2002). Honi lotuta, azken ikerketek mintzamenaren egitura linguistikoen (silabak, sintagmak eta esaldiak) korrelazio neuralak iradoki dituzte. (Ding et al., 2015).

ROI analisi esploratorioak eremu okzipitalek antzeko patroï bat erakutsi dezaketela iradokitzen du: theta sinkronizazio handiagoa gaztelerazko blokeetan ingelesezko blokeetan baino. Bestalde, eremu frontaletan hizkuntza eta saioa faktoreen arteko interakzio posible bat adierazten du analisi honek. Gaztelerako bigarren saiak theta sinkronizazio handiagoa erakusten du lehenengo saiorekin alderatuz gero, baina ingelesezko blokeetan ez da ezberdintasunik ageri. Hala ere, gogoratu behar da emaitza hauek eremu aukeraketak sortuak izan daitezkeela, beraz,

ikerketa gehiago behar da hizkuntza ikasketak thete sinkronizazioan duen eragina aztertzeko.

Alpha eta beta bandak

Burmuin osoko analisiari dagokionez, erreferentzia basearekiko potentzia jaitsiera topatu zen bi hemisferiotako lobulu tenporaletan eta potentzia igoera lobulu fronto-parietal eta okzipitalen eremu dorsaletan. Alpha potentzia jaitsierek zelula piramidalen kitzikakortasun altuko egoerak isladatzen ditzutela uste da, alpha potentzia igoerek kitzikakortasun baxuko egoerak isladatzen dituzten bitartean: inhibizio egoera (Klimesch et al., 2007). Beste batzuek potentzia aldaketa hauek kodifikatzeko gaitasunari egokitzen dizkiote (Hanslmayr et al., 2012): kitzikakortasun altuko egoeratan, zelula piramidalak sinkronia gutxiagoarekin pizten dira, entropia (informazio aberastasun neurgailu bat) igotzen delarik, kodifikatutako informazio kopurua handituz. Kontrako egoeran, kitzikakortasun baxuko egoeratan, entropia txikiagoa da eta kodifikatutako informazioa errepikakorra da (Hanslmayr et al., 2012). Honekin bat eginik, ariketarekin lotutako eremuetan alpha desinkronizazioa (ERD) topatu izan denean, alpha sinkronizazioa (ERS) topatu izan da ariketarekin lotuta ez dauden eremutan (ikus Klimesch et al., 2007, laburpena). Honetaz gain, alpharen eginkizuna informazio aukeraketan aztertua izan da (Zumer et al., 2014). Arreta bisualeko ariketa batean, alpha ERDa topatu zen arreta jarri behar zen objektuarekiko hemisferio kontralateralean eta alpha ERSa hemisferio ipsilateralean. Ondorioz, hemen aurkeztutako lanean topatutako alpha eta beta banden desinkronizazioa informazio prozesamendu egoera bat isladatu dezake, alpha sinkronizazioak inhibizio egoera bat isladatzen duen bitartean.

Hau oinarri bezala hartuz, alpha potentzia jaitsiera eta igoerek bi hemisferioetako lobulu tenporala eta behe-lobulu parietala mintzamenaren prozesamenduan parte hartzen dutela adierazten dute, aurreko ikerketetako modeloekin bat eginik (e.g. Friederici, 2011). Gainera, post-hoc analisek gaztelerak ingelesak baino potentzia aldaketa handiagoak eragiten dituela erakutsi dute. Aurreko ikerketen proposamenak jarraituz, hizkuntza sareko eremuek alpha desinkronizazio handiagoa, beraz informazio prozesamendu handiagoa, erakusten dute Gazteleran (ez ama-hizkuntza) ingelesean baino (ama-hizkuntza). Bestalde saretik kanpo dauden eremuek inhibizio altuagoa erakusten dute gazteleran, ingelesean baino. Honen azalpen posible bat, alpha desinkronizazioa erakusten duten eremuek bateratze sintaktiko eta semantikoa adieraztea da. Nahiz eta nagusiki beta eta gamma bandak izan dira bateratze semantiko eta sintaktikoarekin lotu diren frekuentzia bandak (Bastiaansen and Hagoort, 2006), azkenaldian egindako lanek alpha eta beta desinkronizazioak bateratze semantiko eta sintaktikoaren erlazionatuta daudela proposatu dute (Lam et al., 2016). Lamen arabera, testuinguru indartsuago bat eskaintzen denean

erraztasun efektu batek azalduko luke zergatik eremu batzuk gutxiago hartzen duten parte bateratze prozesuan.

ROI analisi esploratorioak ikasketak bateratze prozesuan parte hartzen duten frekuentzia banda eta burmuin eremuetako aldaketen inguruko ebidentzia mugatuak aurkezten ditu. Ezker lobulu tenporaleko alpha desinkronizazioak aldaketa txiki bat erakusten du lehenengo eta bigarren saioaren artean, baina estatistikek ez dute aldaketa babesten. Ikerketa gehiago behar da hipotesi hau hobeto balioztatzeko.

Bestalde, hizkuntzaren ulermen pasiboa egiten denean eta ariketarik ez dagoenean, alpha desinkronizazioa arreta prozesuak eta portaeraren ondorioak isaladatzen dituela proposatu da (Bastiaansen and Hagoort, 2006), baina ez (derrigorrez) ulermenarekin zuzenean erlazionatutako prozesuak (ikus ere Davidson and Indefrey, 2007). Esperimentu honen kasuan ez dago ariketarik entzumenaren bitartean. Beraz, alpha desinkronizazio indartsuagoak partaideak Gaztelerazko blokean 'sartuagoak' daudela adieraz dezake. Honek, frekuentzia banda guztietan bi hizkuntzen artean topatu diren modulazioen arteko diferentzia handiak azaldu ditzake. Momentu honetan zaila da bereiztea ea topatutako diferentziak ulermenari dagozkion edo arretak eragindakoak diren. Lan gehiago behar da bi egoerak bereizteko. Esperimentu honetan ariketarik ez ezartzeko arrazoa, ariketa batek ulermen prozesuak atzealdeko eremuetara bideratu ditzakeela da (Friederici, 2011). Bideratze hau ez-ama-hiztunetan nola gertatzen den azaltzen duen ikerketarik ez da topatu literaturan. Ariketa batek partaideek arreta jartzen zutela ziurtatuko luke, baina zaila izango litzateke diferentziak nondik datozen jakitea: ea diferentziak ulermenak sortuak diren edota H1ean eta H2an bideraketa ezberdina jasaten delako. Hori dela eta, naturalagoa den entzumen pasiboa aukeratu genuen esperimentu honetarako.

Azkenik, ezin da blokeen ordenaren arazoa zuzenean baztertu. Eztabaida atal honetan aurkitutako efektuak Hizkuntza efektu bezala aztertu diren arren, ezin dugu ahaztu ingelesezko blokea beti gaztelerazko blokearen aurretik egin zela, aldaketa kostua ekiditeko (Costa and Santesteban, 2004). Errazagoa da ama-hizkuntzatik bigarren hizkuntzara pasatzea, bigarren hizkuntzatik ama hizkuntzara pasatzea baino. Horregatik, diseinua kontrabalanzeatuta egongo balitz, gaztelerazko blokeen ondoren burututako ingelesezko blokeetan aldaketa kostu handiagoa izango genuke eta ez zen gehiago ama-hizkuntza entzumen-ulermen erreferentzia garbi bat izango. Hala ere, topatutako emaitzak bloke ordenaren ondorio izanago balira, nekearekin edo estimulu errepikapenarekin topatu ohi diren efektuak ikusi beharko genituzke. Estimulu errepikapena aztertu duten ikerketek, gamma bandaren potentzia jaitziera topatu dute (Grill-Spector et al., 2006). Bestalde, nekea eremu okzipitaletako alpha igoerarekin dago lotua (Von Bünau et al., 2010; Berger, 1929). Ondorioz, esperimentu

honetan topatutako patroiak ez dira bloke ordenak sortua, eta hizkuntza efektu bat direla esan daiteke.

Hizkuntza ikasketari dagokionez, ez da ikasketak eragindako oszilazio aldaketaren ebidentzia indartsurik topatu. Lan honetan aztertutako frekuentzia banden potentziek esaldi osoen erantzuna adierazten dute, mintzamenaren entzumenean gertatzen diren funtzio kognitibo ezberdinak jasotzen dituztelarik (e.g., Friederici, 2011). Honetaz gain, partaideek jaso zuten trebakuntza intentsibo eta espezifikoa, epe-luzean egindako ikastaro batek baino aldaketa apalagoak eragin ditzake. Denbora leiho epe motzago batean egindako analisi bat aldaketa mota hauekiko sentikorragoa izan daiteke.

4.5 Laburpena

Lan honek ama-hizkuntzan eta bigarren hizkuntza batean esaldi ulermenean gertatzen diren oszilazio neuronalen dinamika espazialak aztertu ditu. Ama-hizkuntzan sortutako erantzunak baita hizkuntza berri baten trebakuntza aurretik eta ondoren sortutako erantzunak konparatu ziren. Emaitez theta bandaren potentzia (bi hemisferioetako eremu frontalean eta eskuineko lobulu parietalean) ariketaren eskakizunekin lotutako burmuin eremuetan, sinkronizatu zela erakusten dute. Frekuentzia banda honetan topatutako aldaketek, lexiko berreskurapenak ama-hizkuntza ez den hizkuntza batean eskakizun handiagoa duela erakusten dute. Alpha eta beta bandei dagokienez, diferentzia argia topatu zen ama-hizkuntza eta hizkuntza berriaren artean. Hala ere, erabilitako bloke ordenagatik tentuz interpretatu behar dira diferentzia hauek. Azkenik, ez da ikasketak eragindako oszilazio aldaketarik sostengatu duen ebidentzia indartsurik topatu. Honek, oszilazioak epe-motzeko hizkuntza ikasketa aztertzeke neurgailu desegokia direla adierazi lezake.

5. Kapitulua

H1ean egindako oroimen esperimentua: alfa eta tau erritmoak aztertzen

5.1 Oinarrizko arrazoia

Hizkuntza ikasketak esaldien entzumenean agertzen diren oszilazioetan eragiten dituen aldaketak antzematea zaila dela erakusten du 4. kapituluko esperimentuak. Zailtasun hau, esaldi batean funtzio kognitibo ezberdinak gertatzen direlako gerta daiteke (Friederici, 2011; Hagoort, 2016). Analsiak denbora leiho motzagoetan kontzentratuz gero, oszilazioetan eman litezkeen aldaketa horiek antzematea errazagoa izan daiteke. Kapitulua honetako esperimentuak pausu bat atzera egiten du, eta ama-hizkuntzan (H1) ematen diren oroimen berreskurapenaren mekanismo oszilatarioak aztertzen ditu.

Helduen oroimen berreskuratze mekanismoak aztertzeaz gain, mekanismo hauek nola hobetu ikertzea ere interesgarria da. Adibidez, begiak ixteak oroimen berreskuratzea, gutxienez partaideen ama-hizkuntzan, hobetzen duela ikusi izan da (Vredeveldt, 2011; Vredeveldt et al., 2012).

Zoritxarrez, guk dakigula, begi ixteak oroimenean dakarren onuraren mekanismo neuronalak ulertzeko saiakerarik ez da egin. Oroimen berreskuratzean dituen onuretz gain (Vredeveldt, 2011; Vredeveldt et al., 2012), jakina da begiak ixteak alfa potentzia handitzen duela (Berger, 1929). Bestalde, ariketa kognitibo ezberdinetan erantzun zuzenen kopurua handiatzea lortu da alfa potentzia externoki modulatu denean (Klimesch et al., 2003; Hanslmayr et al., 2005). Hala ere, oraindik ez da ikertu begi-ixteak sortzen duen alfa igoerak oroimen berreskurapenaren mekanismo fisiologikoak nola modulatzten dituen.

Kapitulu honetan azaldutako esperimentua H1ean burututako oroimen episodikoko ariketa bat da, non oroimen berreskuratzea material auditiboekin egin den. Honek berreskuratzea fasea bai begi irekiekin eta bai begi itxiekien egitea baimentzen du. Ondorioz aldi berean 1) alfa erritmoa oroimen episodikoko ariketa auditibo batean nola modulatzeko den eta 2) begi-ixteak (alfa bisualaren modulazioak) eta oroimen berreskuratzea alfa (alfa auditiboa) nola harremantzen diren eta ondorioz portaera nola modulatzeko duen aztertzea ahalbidetzen du.

5.2 Alfa oszilazioak eta oroimena

Alfa 7 eta 13 Hz artean dagoen eta erritmo guztien artean anplitude handiena erakusten duen erritmoa da; M/EEG seinaleetan begi hutsez ikusi daitekeen erritmo bakarrenetakoa da. Hala ere, alfa ez da frekuentzia tarte honetan fluktuatzen duen erritmo bakarra. Aurretiko ikerketek, alfaz gain, 7-13 Hz-ko beste bi erritmo topatu dituzte: mu erritmoa eta hirugarren erritmoa (beranduago tau deitu zena). Mu erritmoa motor eremutan topatzen den oszilazioa da, eta partaideek ariketa motoreak egiten dituztenean desinkronizatzen da (Pfurtscheller et al., 1997). Honen antzera, hirugarren edo tau erritmoa erdi-lobulu tenporalean agertzen da eta mu erritmoarekiko independientea da (Hari, 1993). Tau edo hirugarren erritmo hau, partaideek estimulu auditiboak jasotzen dituztenean desinkronizatzen da (Hari et al., 1997). Klimesch-en arabera tau erritmoa EEGrekin jasotzea zaila da, aldiz, MEG edo kraneo-barneko grabaketekin errazago jasotzen da (Klimesch, 1999). Tau erritmoa EEGrekin jasotzeko zailtasuna, estimulu bisualak erabili dituzten oroimen ariketetan topatutako alfa-efektu ezagunak, estimulu auditibok erabiltzen dituzten ariketetan topatu ez izanaren arrazoia izan daiteke. Adibidez, Krausek oroimen auditiboa aztertzeko bokal antzemate ariketa bat erabili zuen (Krause et al., 1996). Berreskuratze fasean estimuluek alfa desinkronizazioa eragin zuten arren, desinkronizazioa ez zen portaerarekin modulatu. Aurretik egindako ikerketa batean tonu seinaleak erabili zituzten bokalak ordez, eta ez zuten ezta alfa desinkronizaziorik topatu (Krause et al., 1995). Hemen aurkezten den ikerketaren helburua MEGek tau erritmoa jasotzeko duen abantaila erabiliz, oroimen auditiboko ariketa batek tau erritmoa, ea oroimen bisualeko ariketa batek alfa erritmoa modulatzeko duen bezala modulatzeko duen aztertzea da. Gainera, esperimentuak alfa eta tau erritmoak nola harremantzen diren aztertzea ahalbidetzen du.

Epe-motzeko oroimen (e.g. Klimesch et al., 1993), oroimen semantikoko (e.g. Doppelmayr et al., 2005) eta oroimen episodikoko (e.g. Klimesch et al., 1997) ariketen kodifikazio eta berreskuratze faseetan alfa (eta beta) erritmoen desinkronizazioa topatu izan da. Gainera, alfa desinkronizazio magnitudea ariketan emandako

erantzunekin lotua dagoela ikusi da. Klimesch-ek alpha/beta desinkronizazio handiak gaitasun kognitibo eta oroimen gaitasuna adierazten dituela proposatu zuen (Klimesch, 1999). Kodifikazio faseari dagokionez, alfa desinkronizazio handiagoa topatu izan da ondoren gogoratu diren hitzetan ondoren ahaztu diren hitzetan baino (ondorengo memoria efektu izenarekin ezaguna da) (Klimesch et al., 1997; Hanslmayr et al., 2012). Berreskuratze faseari dagokionez, alfa desinkronizazio handiagoa topatu da ariketa ondo egin duten partaideetan (hitz gehiago gogoratu dituzten partaideak), ariketa eskasago egin dutenetan baino (hitz gutxiago gogoratu dituzten partaideak, Klimesch et al., 1993). Alfa desinkronizazio handigoek eta erantzun hobeei duten lotura oroimen ariketa ezberdinetan (epe-motzeko, semantiko eta episodikoetan) topatzeaz gain (ikus Klimesch, 1999; Hanslmayr et al., 2012, 2016), biraketa mentala bezalako bestelako ariketa kognitiboetan ere topatu izan da (Klimesch et al., 2003; Hanslmayr et al., 2005).

Bestalde, estimulu bati erantzunez sortzen den alfa desinkronizazioaren magnitudea, estimulu aurreko bitartean zegoen alfa potentzia absolutuan menpe dago: estimulu aurreko bitartean alfa potentzia absolutua handiagoa bada, estimulu ondorengo alfa desinkronizazioa handiagoa da. Aurreko paragrafoan azaldu den bezala, alfa ERD handiagoak ariketa emaitza hobeei lotu izan da ariketa mota ezberdinetan. Bi gertaera hauetaz baliatuz, Klimeschek alfa potentzia modulatu zuen biraketa mentaleko ariketa batean (Klimesch et al., 2003). Erreferentzia basea bitartean alfa potentzia handitu zuten TMS erabiliz; honek estimulu ondorengo alfa desinkronizazio handiagoa ekarri zuen eta ondorioz, ariketaren emaitzak hobetu ziren. Ikerketa honen antzera, Hanslmayer-ek Neuro Feedback Training metodoa erabili zuen erreferentzia baseko alfa potentzia absolutua handitzeko (Hanslmayr et al., 2005). Emaitzak Klimeschen antzekoak dira: erreferentzia basean alfa potentzia absolutu handiagoak estimulu ondorengo alfa desinkronizazio handiago bat eragin zuen eta ariketaren emaitzak hobetu ziren.

Nahiz eta alfak oroimenean duen eragina eta begi-ixteak alfa okzipitala handitzen duen ikerketa ugari dauden, oraindik begi-ixteak sortutako alfak oroimenean parte hartzen duten oszilazioetan nola eragiten duen ez da aztertu. Hala ere, askotan aurkitu izan da begi-ixteak oroimen berreskuratzean onura dakarrela (Glenberg et al., 1998; Wagstaff et al., 2004; Perfect et al., 2008, 2011; Vredeveldt, 2011; Vredeveldt et al., 2011, 2012). Ikerketa hauek begiak-ixteak ingurutik deskonektatu eta oroimenetik berreskuratutako esperientzia kopurua handitzen dituela erakusten dute.

Begi-ixteak oroimen berreskuratzean duen onura azaltzeko bi hipotesi nagusi aurkitu daitezke. Lehenengoa, karga kognitiboaren hipotesia da, begiak ixtean karga kognitiboa gutxitu egiten dela eta ondorioz oroimen berreskuratze hobetzea

gertatzen dela dio (Perfect et al., 2008, 2011). Bigarrena, modalitate espezifikoko hobekuntza da, begiak-ixteak interferentzia bisualak gutxitu egiten dituela, irudikapena ahalbidetuz eta ondorioz oroimena hobetuz (Vredevelde et al., 2011, 2012). Hala ere, alfak oroimenean duen eragina, begi-ixteak sortzen duen alfa potentzia handitzea eta begi-ixteak oroimenean duen eragina harremandu gabe jarraitzen dute.

5.3 Metodo eta Materialak

Adierazpen etikoa

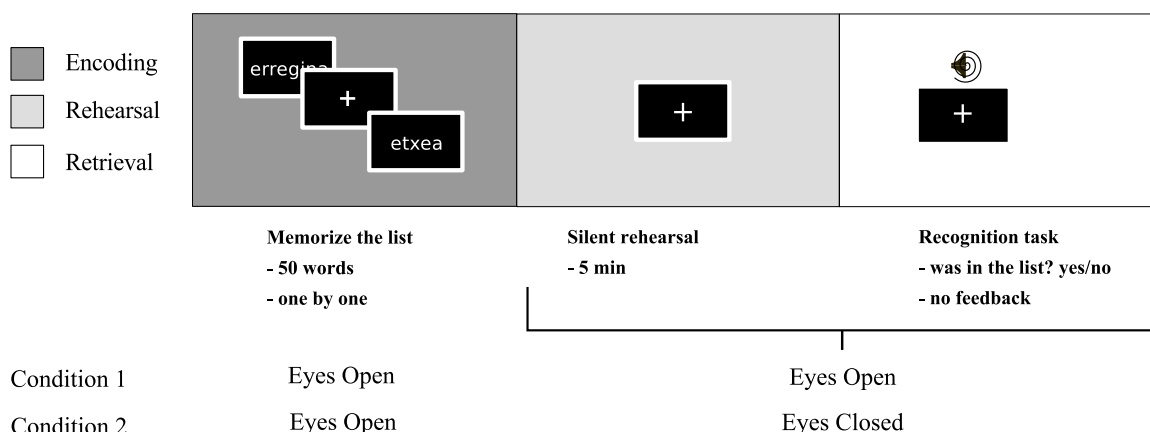
Ikerketa hau Basque Center for Cognition, Brain and Language-n egin da eta bertako etika komiteak onartua da.

Partaideak

Partaideak irakurketa eta entzumen arazorik ez zuten 21 (10 emakume, 11 gizon) Euskarazko ama-hiztun osasuntsu eta eskuinak izan ziren. Partaideak Donostialdean bilatu ziren. Esperimentua hasi aurretik, partaide guztiek idatzizko kontsentimendua eman zuten (Declaration of Helsinki) eta interferentzia magnetikoen bila miatuak izan ziren. 21 partaide hauetaz gain, bi partaide gehiagoren datuak jaso ziren, baina analitiko baztertuak izan ziren batek aginduak ez jarraitzeagatik eta besteak esperimendu bitartean lo hartzeagatik.

Diseinua eta Materialak

Partaideen oroimen gaitasuna bederatzi bloke dituen antzemate ariketa bat burutuz neurtu zen. Bloke bakoitzak hiru fase zituen: kodifikazioa (50 entsaio), errepassoa (5 min) eta berreskuratzea (50 entsaio) eta 11 minutu inguru irauten zituen. Kodifikazio fasean, atzera-proiektzio pantaila batean banan banan idatzizko hitzak aurkeztu ziren eta partaideek hitz hauek irakurri eta ikasi behar zituzten. Errepasso fasean, partaideek hitz hauek bere buruan errepassatu behar zituzten. Berreskuratze fasean, partaideek hitzak entzun eta hasierako zerrendako hitzak antzeman behar zituzten. Hitza zerrendakoa zela uste bazuten botoi berdea sakatuz, edo kontrako egoeran, botoi gorria sakatuz. Partaide bakoitzak ariketa bi egoera ezberdinetan burutu zuen. Blokeen erdietan errepasso eta berreskuratze faseak begi itxiekin egin ziren (EC) eta beste bloke erdietan begi irekiekin (EO; ikus 5.1 irudia). EC eta EO blokeak partaideen artean kontrabalanzeatuak izan ziren.



5.1. irudia: Esperimentuaren diseinua. Lehenengo fasea (kodifikazioa) beti begi irekiekin burutu zen, eta estimulu bisualak erabiliz. Bigarren (errepassoa) eta hirugarren (berreskuratzea) faseak bi egoeratan burutu ziren: begi itxiekin eta begi irekiekin, estimulu auditiboak erabiliz.

Partaideek ariketa Euskaraz burutu zuten, eta zerrenda bakoitzeko hitzak ezaugarri antzekoak zituzten hitz multzo handiago batetik ausaz aukeratua izan zen: frekuentzia ($\log_{10}(\text{freq})$, $\text{mean}=1.02$; $\text{std}=0.69$) luzera ($\text{mean}=7$; $\text{std}=2.06$) eta silaba kopurua ($\text{mean}=4$; $\text{std}=0.95$). Hitz guztiak egunerokotasuneko objektuak adierazten zituzten izen konkretu eta irudikagarriak ziren.

Kodifikazio fasean partaideei hitzak isiltasunean irakurri eta ikasteko adierazi zitzairen. Hitzak banan banan aurkeztu ziren pantaila beltz batean. Hitz bakoitza bi segunduz agertu zen pantailan.

Errepaso fasea bost minutuko iraupena zuen eta partaideei kodifikazio fasean ikasitako hitzak errepassatzeko eskatu zitzairen. Esperimentua hasi aurretik partaideei ondorengoa eskatu zitzairen: errepaso fasean partaideek beraien burua distrahituta zegoela ohartu bezain laster berriz ere zerrenda errepassatzen hasteko.

Berreskuratze fasean, partaideek 50 hitz entzun zituzten (25 gogoratzeko, 25 baztertzeke). Hitz entzuten zutenetik kontatzen hasita bost segundu zituzten hitza antzeman edo baztertzeke. Denbora tarte horretan ez bazuten erantzunik ematen hurrengo hitza aurkezten zen. Erantzun bat ematerakoan, bost segunduetara iristeko soberan zuten denbora itxoin behar zuten hurrengo hitza entzun aurretik. Erantzun bat baino gehiago ematen bazuten, soilik lehenengo erantzuna hartzen zen kontutan.

Prozedura

Datuak 306-kanaleko Elekta Neuromag Elekta (Oy, Helsinki, Finland) ekipamendua erabiliz Donostiako Basque Center on Cognition Brain and Language-k

duen MEG laborategian bildu ziren. MEG ekipamendua inguruko eremu magnetikoak blokeatzen dituen gela-pantailatu batean kokatua dago (passive shielding; Vacuumschmelz GmbH, Hanau, Alemania).

Partaideei grabaketa bitartean postura eroso hartu eta erlaxatzeko eskatu zitzaion datu grabaketa bitartean mugimenduak ekiditeko asmoz. Ariketen bitartean begi, buru eta gorputz mugimenduak saihesteko eskatu zitzaion ere. Bi elektrookulograma (bertikala eta horizontala) eta elektrokardiograma sinple bipolar bat jaso ziren ere, ondoren ICA bidezko artefaktu baztertzea gauzatu ahal izateko. Ondoren bi minutuko bi atsedeen bloke grabatu ziren, bat begi itxiekien eta bat begi irekiekien.

Buruaren forma digitalizatzeko Polhemus Isotrak (Polhemus, Colchester, VM, EEBB) boligrafo bat erabili zen. Buruaren forma digitala partaide bakoitzaren burua bere irudi estrukturalari (T1 irudia) lerrokatu ahal izateko erabili zen. Honetaz gain, partaidearen buruan buru-lokalizaziorako 5 espira kokatzen dira, eta hauen kokalekua fiduzialekiko jasotzen da. Bost espirak MEG grabaketa bitartean aktibo daude, buruaren lokalizazio jarraia ematen dutelarik (cHPI). MEG datuak Elekta ekipamendu batean berezko softwarean bidez, 1000 Hz lagintze-abiadura, 0.03 Hz goi-paseko iragazkia eta 330 Hzko behe-paseko iragazkia erabiliz jaso ziren.

Datu Analisiak

Lehenengo blokearen helburua partaideak ariketa ezagutu eta MEG-laborategira egokitzea izan zen. Ondorioz, analisisetatik baztertu egin zen eta beste zortzi blokeen datuak erabili ziren.

Portaera analisisia

Antzemate zuzena izandako entsaio kopuruaren ratioa Laplacen hurbilekta erabiltzen duen maila anitzeko erregresio lineal orokortu batekin (Dixon, 2008) modelatu zen begi faktorea erabiliz (irekiak, itxiak). Bi modelo konparatu ziren, lehenengoa partaideen ausazko efektua interzepzioarentzat kontuan hartzen zuena ($m1 = \text{Hit} \sim \text{Eyes} + (1 + |\text{Sbj}|)$) eta bestea partaideen ausazko efektua begi faktorean kontuan hartzen zuena ($m2 = \text{Hit} \sim \text{Eyes} + (1 + \text{Eyes}|\text{Sbj}|)$).

MEG data

MaxFilter 2.2 erabilita MEG datuak Espazio Seinale Banaketa tenporalarekin (temporal Signal Space Separation tSSS) iragazki ziren lau segunduko denbora leihoa eta 0.98ko korrelazio minimoa erabiliz. Partaide bakoitzaren buruaren jatorria eta

sensore zaratatsuen zerrenda eskuz markatu ziren, datuen lagintze-abiadura 250 Hz jaitsi zen eta linea elektrikoaren frekuentzia (50 Hz) eta honen harmonikoak iragazki ziren. MRC Cognition and Brain Science Unitek duen MEG laborategiaren gomendioak jarraituz, lagintze-abiadura jaitea eta iragazketa bi pausu ezberdinetan egin zen, softwareak duen akats baten ondorioz datuen kutsadura ekiditzeko (http://imaging.mrc-cbu.cam.ac.uk/meg/Maxfilter_V2.2). Partaide bakoitzaren buruaren kokalekua, kokaleku lehenetsira transformatu zen, partaide eta blokeen artean buru kokaleku amankomuna zegoela ziurtatzeko. Datuak Fieldtrip tresna erabiliz prozesatu ziren (20141202 bertsioa, Oostenveld et al., 2011).

Lehenbizi, berreskuratze faseko datuak segmentutan moztu ziran. Segmentuaren hasiera hitzaren hasierara lotu zen. Datuak bost segunduko luzeran moztu ziren, bi segundu hitza hasi aurretik eta hiru ondoren.

Ondoren, artefaktuak bilatzeko datuak ikuskatu ziren: z-balioa 20 tik gora zuten segmentuak automatikoki baztertuak izan ziren. Segmentu bakoitza 12 segundutara iritsi arte zero-betegarriekin luzatu zen. 40 Hz-tan ezarritako behe-paseko FIR iragazki bat (zero-faseko pasada bakarra) erabili zen, eta 200 ms-ko (-200 - 0 ms) erreferentzia zuzenketa egin zen.

Datuak Konponente Independienteen Analisia (ICA) algoritmoa erabiliz deskonposatu ziren. Konponente kopurua, gradiometro kopurura berdindu zen (204) eta analisi honen aurretik ez zen dimentsio murrizketa algoritmorik erabili. fastICA algoritmoa erabili zen konbinatu gabeko gradiometrotan (204 sensore). Ondoren, ICA konponente bakoitza HEOG; VEOG eta EKG seinaleekin korrelatu zen. Hiru desbideratze tipikotik gorako korrelazioa erakutsi zuten konponenteak baztertu egin ziren eta, ondoren, konponenteak jatorrizko sensore espaziora transformatu ziren.

Begi itxien efektua

Hasteko, atsedean blokean eta berreskuratze fasean begiak ixtean sortutako alfa potentzia modulazioa konparatu zen. Horretarako, atsedean blokeetako (begiak irekita eta itxita) lehenengo 30 segunduak erabili ziren. Honetaz gain, berreskuratze faseko begi itxiekin egindako lehenengo blokeko eta begi irekiekin egindako lehenengo blokeko hasierako 30 segunduak jaso ziren. Potentzia balioak frekuentzia-menpeko luzera duen Hanning leiho sinple bat erabilita egin zen. Denbora leiho bakoiztean 6 ziklo zeuden, segundu bateko pausuekin. Analisia segmentu guztian burutu zen (30 s) 0 eta 40 Hz artean hertzio bateko pausuekin. Honek 10 Hz-tara 1.7 Hz-ko frekuentzia leuntzea dakar. Potentzia balio absolutuak erabili ziren analisi honetarako. Ondoren, gradiometroak konbinatu eta konbinatutako gradiometroetan burutu ziren analisi estatistikoak.

Begien itxieraren efektua neurtzeko alfa bandaren inguruan analisi estatistikoa burutu zen. Sensore espazioan, ausazko mulkoen permutazio (1000 permutazio) analisia erabili zen (Maris and Oostenveld, 2007) (frekuentzia eta denbora puntu guztien batezbesteko potentzia erabili zen) bi egoeren artean alfa bandan (7-13 Hz) diferentzia esanguratsuak zeuden edo ez neurtzeko. Sensore bakoitzeko t-estatistikak kalkulatu eta algoritmoak sensore mulkoak topatu zituen. Bizilagun deskribapena Fieldtrip-ek eskaintako Neuromag-306 plantilan oinarritua zegoen. Datu puntu bat mulko baten parte izateko, $p < 0.05$ (bi aldeko proba eta probabilitate zuzenketa erabiliz) ataka pasa eta gutxienez bi bizilagun izan behar zituen. Mulko baten t-estatistikak gehiketa mulkoaren estatistika balio bezala hautatu zen (maxsum aukera Fieldtrip-en), eta 1000 permutazioko ausazko proban erabili zen.

Denbora-frekuentzia analisia

Konparaketa honen ondoren, berreskuratzearen dinamikak aztertu ziren. Potentzia balioak frekuentzia-menpeko luzera duen Hanning leiho simple bat erabilita kalkulatu ziren. Denbora leiho bakoitzean 6 ziklo zeuden, 0.05 s-ko pausuekin. Analisia segmentu osoan burutu zen (-2 eta 3 s artean) 0 eta 40 Hz artean hertzio 1-eko pausuekin. Honek 10 Hz-tara 1.7 Hz-ko frekuentzia leuntzea dakar. Denbora-frekuentzia puntu bakoitzeko potentzia balioak erreferentzia basearekiko (-0.5,0) normalizatu ziren. Ondoren, gradiometroak konbinatu eta konbinatutako gradiometroetan burutu ziren analisi estatistikoak.

Mugatutako analisi estatistikoa

Alfa bandaren a priori analisi bat egin zen sarreran aipatutako hipotesia aztertzeko: berreskuratze fasean alfa ERDa handiagoa da gogoratutako hitzetan ahaztutako hitzetan baino. Gainera, begi itxiek alfa ERD handiagoa eragin beharko lukete begi irekiekin alderatuta. Analisi estatistikorako, ausazko mulkoen permutazio (1000 permutazio) analisia burutu zen (Maris and Oostenveld, 2007) alfa bandan (7-13 Hz) eta (-0.5, 2) s-ko denbora leihoan. Beste parametro guztiak aurreko analisiaren berdinak dira.

Mugatu gabeko analisi estatistikoa

Azkenik, aurreko analisia osatzeko eta beste frekuentzietan egon zitezkeen efektuak aztertzeko helburuarekin mugatu gabeko analisi bat burutu zen. Ausazko mulkoen permutazio (1000 permutazio) analisia burutu zen (Maris and Oostenveld, 2007) frekuentzia puntu guztietan eta (-0.5, 2) s-ko denbora leihoan. Beste parametro guztiak aurreko analisiaren berdinak dira. the parameters remain the same as in the

previous statistical analyses.

Iturri analisia

Iturriak berreraikitzeke Dynamic Imaging of Coherent Sources (DICS) (Gross et al., 2001) metodoa erabili zen. MRI egitura irudiak larruazal, garezur, burmuin eta CSF mintzetan segmentatu zen, eta geruza bakarra modelo erabiliz burmuinaren bolumenari eroaltasun balio bat eman zitzaion (Nolte, 2003). Bolumenaren eroaltasun modelo eta burmuin osoa estaltzen zuen 8 mm-ko lauki-sare erregular (spatial grid) bat (Fieldtripen eskuragarri) erabili ziren leadfield-ak kalkulatzeko. Zehar-espekto dentsitate matrizeak kalkulatu ziren 10 Hz ren inguruan (3 Hz-ko frekuentzia leuntzearekin) intereseko hiru denbora leihoentzat (0.5 1), (1. 1.5) eta (1.5 2) s. Denbora leiho bakoitzeko, 4 egoeretako amankomunak ziren, iragazki espazialak sortu ziren leadfield-ak eta zehar-espekto dentsitate matrizeak erabiliz. Ondoren, datuak iragazki amankomunak erabiliz iragazi ziren eta erreferentzia basearekiko potentzia erlatiboak kalkulatu ziren egoera bakoiztean.

Analisi estatistikorako, ausazko mulkoen permutazio (1000 permutazio) analisia burutu zen (Maris and Oostenveld, 2007) denbora leiho bakoitzeko (0.5 1), (1. 1.5) eta (1.5 2) s. Beste parametro guztiak aurreko analisiaren berdina dira.

5.4 Emaitzak

Portaera analisia

5.1 taulak erakusten duen bezala, modeloak partaideen erantzun zuzenen ratioa 0.75 inguru dagoela eta bi egoeren artean diferentziarik ez dagoela adierazten du. Bi modeloak konparatu zirenean, partaideen ausazko efektua begi faktorean ez zuen onurarik ekarri ($\text{Pr}(>\text{Chisq})=0.96$). Horregatik, soilik lehenengo modelo azaltzen da.

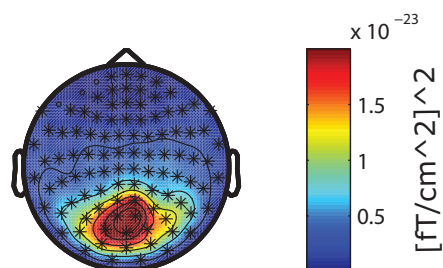
	m1
Eyes Closed	0.75 (0.70, 0.79)
Eyes Opened	0.76 (0.67, 0.82)

5.1. taula: Zuzenki atzemandako entsaioen ratioa (%95 CI). Lehenengo modeloaren estimazioak eta hauen konfiantza tartea (CI) adierazten dira ($m1 = \text{Hit} \sim \text{Eyes} + (1 + 1|\text{Sbj})$).

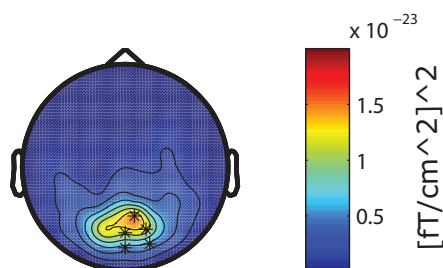
(hbt)

Alpha band power (Eyes Closed - Eyes Open)

a) Resting State



b) Retrieval Phase



5.2. irudia: Alfa bandan (7-13 Hz) begi itxien eta irekien arteko potentzia absolutuaren diferentzia (a) atsedean blokean eta (b) berreskuratze fasean. Kolore epelek begi itxietan potentzia handiagoa dela adierazten dute, kolore hotzen bi egoeren artean diferentzia txikia edo ia diferentziarik ez dagoela adierazten dute. Asteriskoek analisi estatistikoan ageri den mulkoaren parte diren sensoreak adierazten dituzte.

MEG datuak

Begi itxien efektua

5.2 irudiak begi itxi eta irekien artean alfa bandan (7-13 Hz) dagoen potentzia diferentzia irudikatzen du (a) atsedean blokean eta (b) berreskuratze fasean. Nahiz eta bi irudiek topografia antzekoa erakusten duten (alfa altuagoak begi itxientzat atzealdkeo sensoreetan), berreskuratze fasean begi itxien eta irekien arteko diferentzia txikiagoa da (ikus kolore barrak). Analisi estatistikoak mulko positibo bat erakutsi zuen atsedean blokean (clusterstat=343.5; $p < 0.001$) eta estaitsikoki ia esanguratsua den beste mulko positibo bat berreskuratze fasean (clusterstat=11.91; $p=0.073$).

Denbora-frekuentzia analisisia

Mugatutako analisi estatistikoa

5.3 irudiak batezbesteko denbora-frekuentzia grafikoak erabiltzen ditu oszilazio potentzia analisiak irudikatzen. Batezbesteko orokorra (5.3i irudia) hitz-estimulu batentzat ohikoa den erantzuna erakusten du: theta ERSa 0 eta 0.5 s artean eta alfa ERDa 0.5 eta 1 s artean eta azkenik alfa-altua/beta errebote bat 1 eta 2 s artean. Patroi

hau egoera guztietan (begi itxi eta irekietan) eta elementu guztietan (gogoratutako eta ahaztutako hitzetan) topatu zen. Beraz, aurrerago azaltzen diren ezberdintasunak orain azaldutako patroiaaren modulazioak dira. Behean azaltzen den bezala, ERD modulazioak elementu motaren arabera topatu dira (gogoratutako eta ahaztutako hitzak) eta ERS modulazioak egoeraren arabera topatu dira (begi itxi eta irekiak).

Egoera ezberdinak konparatzean, espero zen memoria efektuarekin bat datoz datuak: gogoratutako elementuak ahaztutako elementuek baino alfa ERD handiago bat erakusten dute, bai begi itxiek eta bai begi irekiek. Begi itxietan, alfa bandan (7-13 Hz) egindako analisi estatistikoak 0.6 eta 1.75 s artean irauten duen mulko esanguratsu bat erakusten du (5.3g irudia). Begi irekietan, 0.65 eta 1.65 s artean mulko esanguratsu bat (clusterstat=-1470; p=0.006) agertzen da (5.3h irudia).

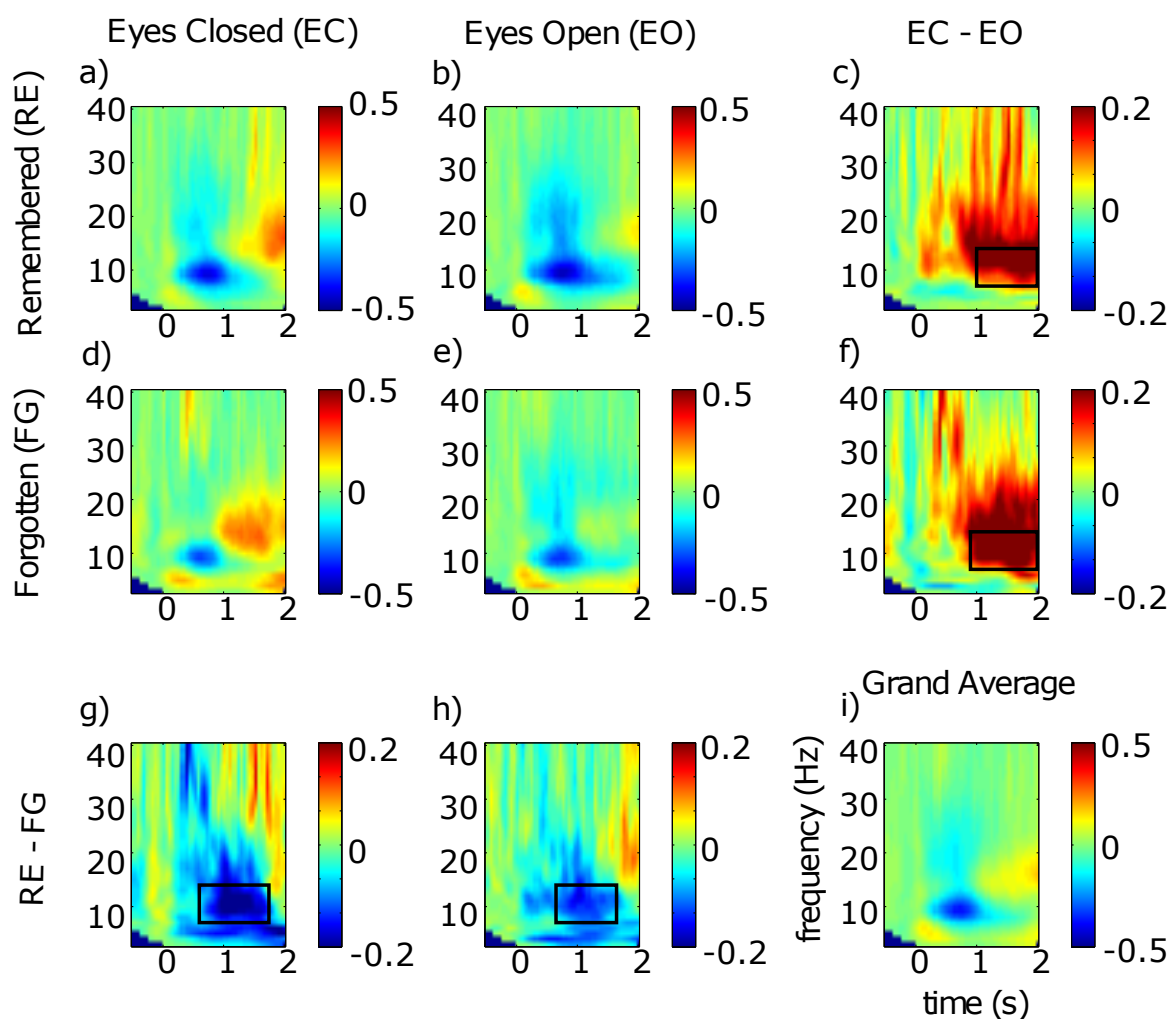
Honetaz gain, begi itxien efektu bat topatu zen ere. Bi elementu motetan (gogoratutako eta ahaztutako hitzetan) begi itxiek, begi irekietan alderatuta, alfa potentzia altuagoa erakutsi zuten 1 eta 2 s artean. Gogoratutako hitzetan, mulko esanguratsu bat (clusterstat=1401; p=0.02) aurkitu zen 1 eta 2 s artean (5.3c irudia). Ahaztutako hitzetan beste mulko esanguratsu bat topatu zen 1 eta 2 s artean (5.3f irudia).

Patroi hauen topografia era simple batean irudikatzeko efektua segundu-erdiko hiru leihotan banatu zen: lehenengoa 0.5 eta 1 s artean (ikus 5.4 irudia), alfa ERD indartsuena ageri den leihoa; bigarrena, trantsizio leihoa, 1 eta 1.5 s artean (ikus 5.5 irudia), oroimen konparaketaren alfa ERDa oraindik ageri eta adli berean konparaketaren alfa ERSa agertzen hasia den denbora leihoa, eta azkenik, hirugarren leihoa (ikus 5.6 irudia), 1.5 eta 2 s artean, non begien konparaketaren alfa ERS nabaria den eta oroimen konparaketako alfa ERDa ahulagoa den.

Topografia irudien arabera, hasierako fasean (0.5 - 1 s) oroimen efektua ia sensore guztietan ikusten den alfa ERD sakabanatu bat bezala agertzen da, nahiz eta nagusiki efektua eskuineko sensore tenporaletan nabarmentzen den (ikus 5.4 g eta h irudiak). Sensoreen kokalekuaren arabera oroimen efektuaren oinarria ezberdina da: Sensore batzuetan ERS txikiago batek, eta beste batzuetan ERD handiago batek, sortua da. Denborak aurrera egin ahala, efektua bi hemisferiotako sensoreetan mantentzen da soilik (ikus 5.5 g eta h, eta 5.6 g eta h irudiak). Bestalde, ERS efektua atzealdeko sensore eta sensore parietaletan topatzen da nagusiki (ikus 5.4, 5.5 eta 5.6, c eta f irudiak). Nahiz eta topografia ez den aldatzen, denboran aurrera joan ahala efektuaren magnitudea handitzen doa.

Interakzioak neurtzeko analisi estatistikoak burutu ziren. Analisi batean begi itxiek (begi itxiak eta begi irekiak) elementu motan (gogoratutakoak – ahaztutakoak)

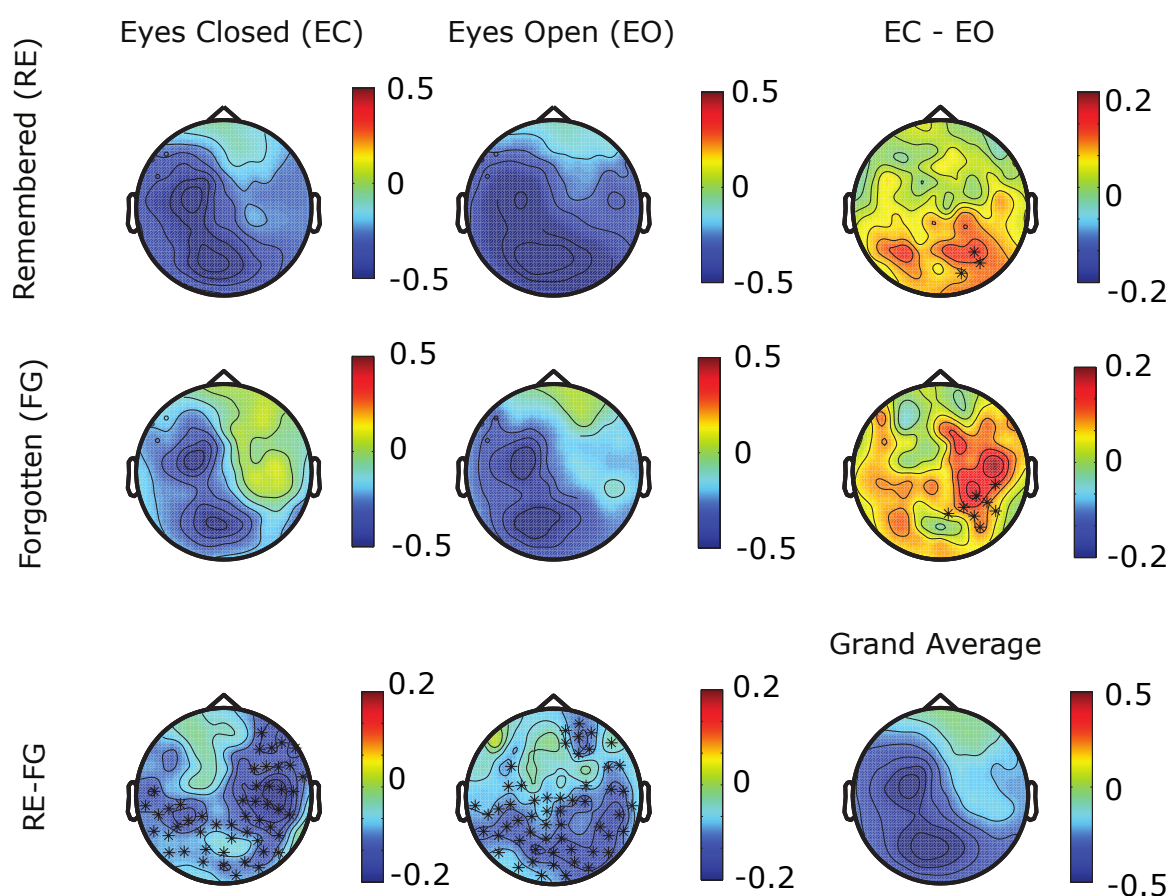
Restricted Oscillatory Power Analysis



5.3. irudia: Erreferentzia basearekiko (-0.5 - 0) s potentzia aldaketa erlatiboa denbora eta frekuentzietan zehar. Lehenengo lerroak gogoratutako hitzen potentzia aldaketak erakusten ditu, eta bigarrenak ahaztutako hitzenak. Lehenengo zutabeak begi itxien potentzia aldaketak irudikatzen ditu, eta bigarrenak begi irekienak. Hirugarren lerro eta zutabeak ondoko bi egoeren diferentziak irudikatzen ditu. Eta behe-eskuinean dagoen grafikoak batezbesteko orokorra irudikatzen du. Kolore hotzek ERDA irudikatzen dituzte eta epelek ERSak.

Restricted Analysis Power Topography

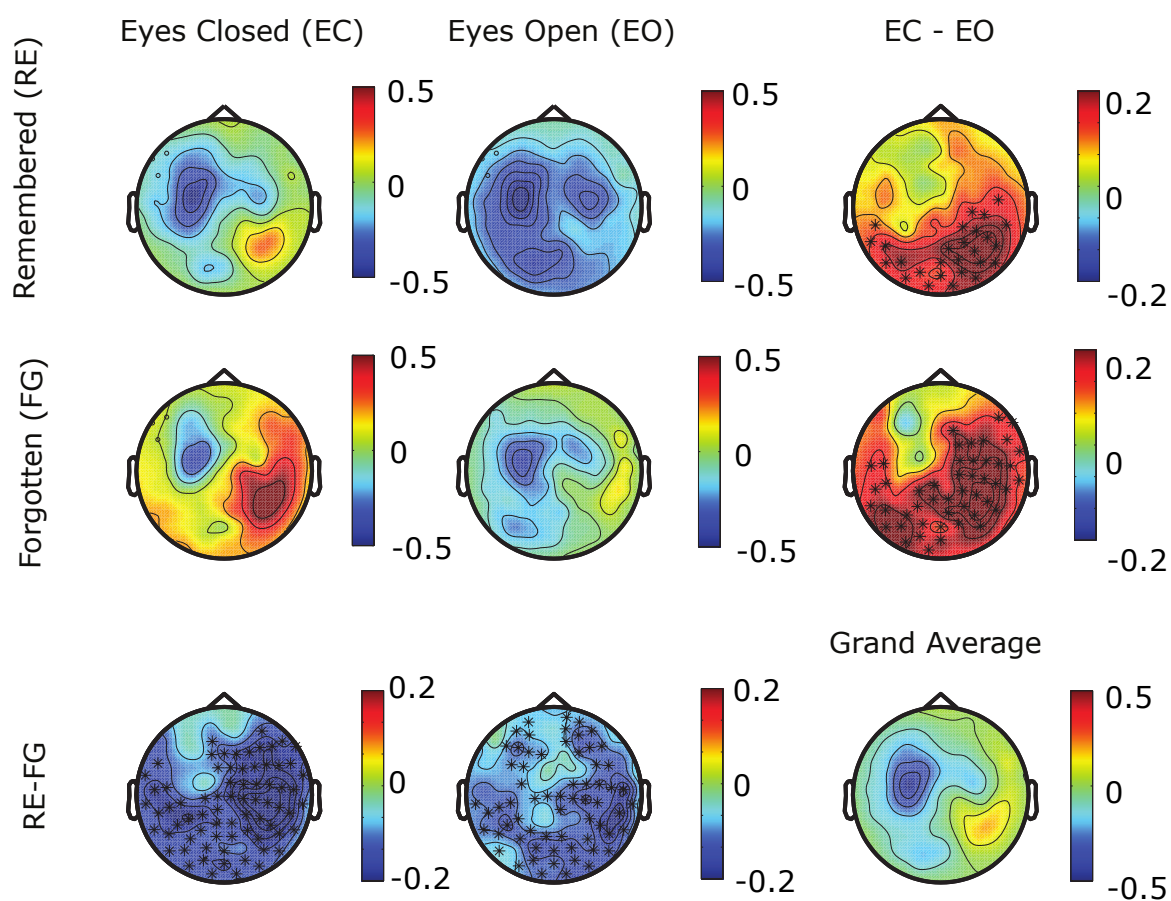
Freq: 7-13 Hz / Time window: 0.5-1 s



5.4. irudia: Alfa bandaren (7-13 Hz) topografia 0.5 eta 1 s artean. Irudi hauen eskemak 5.3. irudiaren eskema jarraitzen du. Topografia grafiko bakoitzak konbinatutako gradiometroen erreferentzia basearekiko alfa (7-13 Hz) potentzia erlatiboa irudikatzen du. Asteriskoek konparaketa bakoitzean mulko esanguratsuen parte diren sensoreak markatzen dituzte. Kolore eskala 5.3 irudiaren berdina da.

Restricted Analysis Power Topography

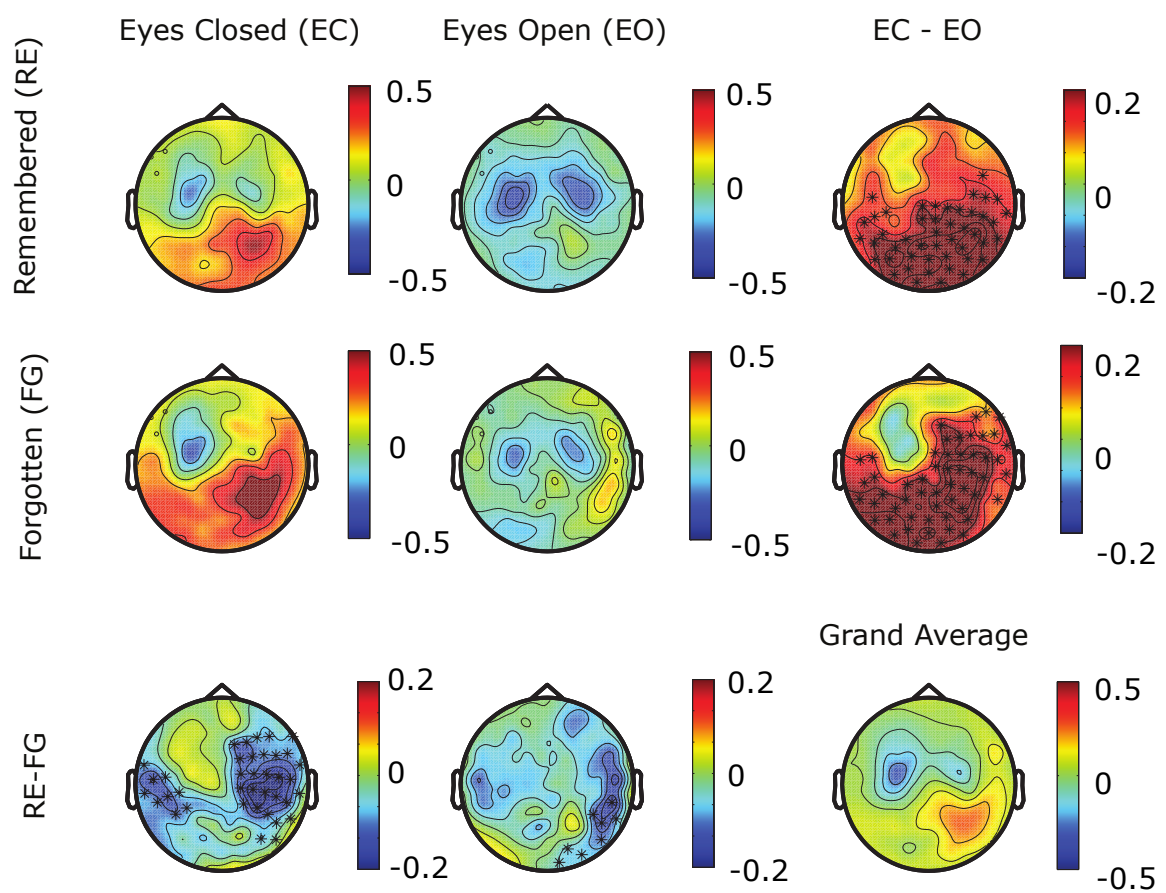
Freq: 7-13 Hz / Time window: 1-1.5 s



5.5. irudia: Alfa bandaren (7-13 Hz) topografia 1 eta 1.5 s artean. 5.4 irudiaren eskema jarraitzen du.

Restricted Analysis Power Topography

Freq: 7-13 Hz / Time window: 1.5-2 s



5.6. irudia: Alfa bandaren (7-13 Hz) topografia 1.5 eta 2 s artean. 5.4 irudiaren eskema jarraitzen du.

eragiten duen modulazioa neurtu zen. Beste analisi batean elementu motak (gogoratutakoak eta ahaztutakoak) begi itxietan (begi itxiak – begi irekiak) eragiten zuen modulazioa neurtu zuen, BI analisisetako batek bera ere ez zuen interakzio esanguratsurik topatu ($\text{abs}(\text{clusterstat}) < 259$; $p > 0.7$).

Mugatu gabeko analisi estatistikoa

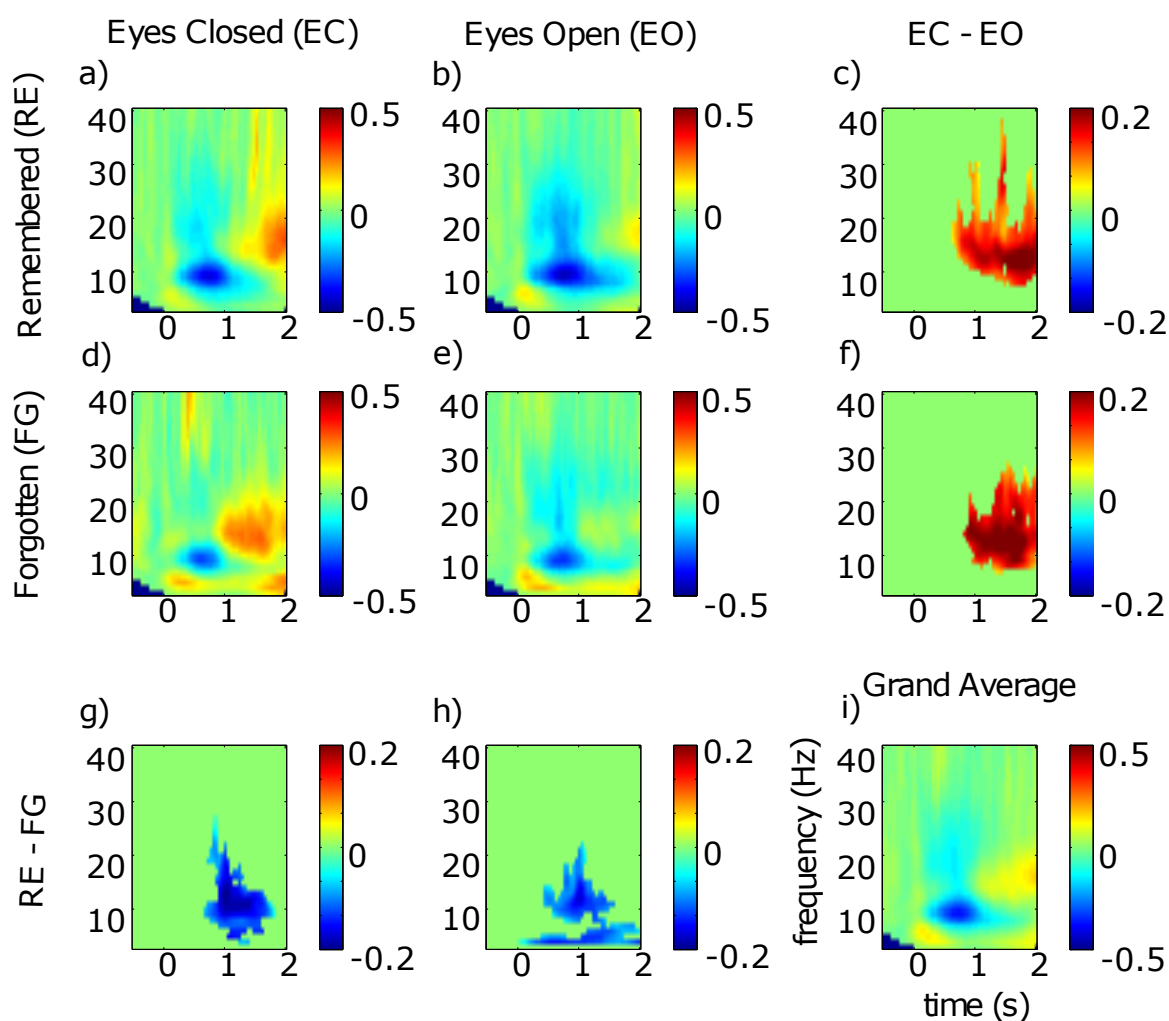
Mugatu gabeko analisisian, a priori analisisian egindako eskema jarraitu zen, baina analisisia alfa bandara mugatu orde 3 eta 40 Hz bitarteko frekuentzia guztietan neurtu zen. 5.7, 5.8, 5.9 eta 5.10 irudiek, 5.3, 5.4, 5.5 eta 5.6, irudien eskema jarraitzen dute hurrenez hurren.

Emaitzak alfa frekuentzia bandara mugatutako analisisien emaitzen oso antzekoak dira: gogoratutako hitzek ahaztutako hitzek baino ERD handiagoa erakusten dute, eta begi itxiek begi irekiek baino ERS handiagoa. Begi itxietan, analisi estatistikoak mulko esanguratsu bat ($\text{clusterstat} = -8281$; $p = 0.002$) erakusten du 4-27 Hz eta 0.65-1.8 s artean (ikus 5.7g irudia). Begi irekietan, analisiak beste mulko esanguratsu bat ($\text{clusterstat} = -7357$; $p = 0.004$) erakusten du 4-22 Hz eta 0-2 s artean (ikus 5.7h irudia). Nahiz eta efektuak begi itxiekin topatutako baino denbora leiho luzeagoa hartu, leiho luzapen hau theta frekuentzia baxuetan gertatzen da soilik. Beste frekuentzia guztietarako denbora leihoa begi itxiekin topatutako denbora leihoaren oso antzekoa da.

A priori egindako alfa analisiaren begi itxieraren efektu antzekoa, baina frekuentzia banda zabalagoa batean topatu zen. Bi hitz motentzat (gogoratutakoak eta ahaztutakoak) begi itxiek, begi irekiekin alderatuta, alfa ERS handiagoa eragiten zuten 0.6 eta 2 s artean. Honetaz gain, beta ERS efektu antzekoa topatu zen. Gogoratutako hitzetan, analisi estatistikoak mulko esanguratsu bat ($\text{clusterstat} = 14766$; $p = 0.01$) topatu zuen 8-38 Hz eta 0.6-2 s artean (ikus 5.7c irudia). Ahaztutako hitzetan, mulko esanguratsu bat ($\text{clusterstat} = 13840$; $p = 0.006$) topatu zen 7-27 Hz eta 0.8-2 s artean (ikus 5.7f irudia). Analisi honek, alfa bandaz gain, berreskuratze fasean, begiak ixteak beta banda ere modulatzeko duela erakusten du. Bestalde, oroimen eta begi itxien efektuen denbora leihoez mugatutako analisisian baino gainjartze handiagoa erakusten dute.

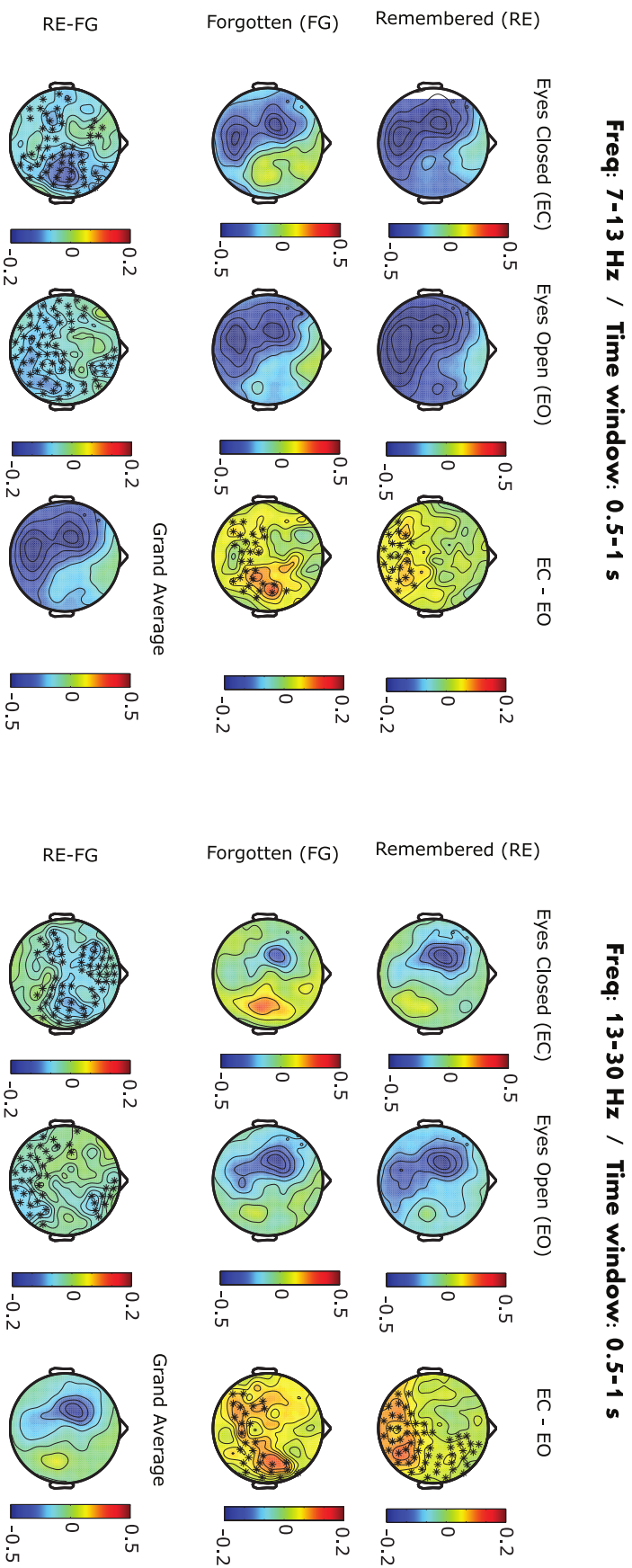
Topografia irudien arabera, hasierako fasean (0.5 - 1 s) oroimen efektua alfa bandan topatzen da gogoratutako hitzek ERD handiagoa edo ERS ahulagoa erakusten dutelako, bai begi itxiekin bai begi irekiekin. Mugatutako analisiarekin konparatzerakoan, mugatu gabeko analisiak beta banda ere hartzen du. Mugatutako analisisaren antzera, efektuaren magnitude handiena sensore tenporaletan topatzen da (see ikus 5.8, 5.9 eta 5.8, g eta h irudiak). Bestalde, begi itxien efektua alfa eta beta

Unrestricted Oscillatory Power Analysis



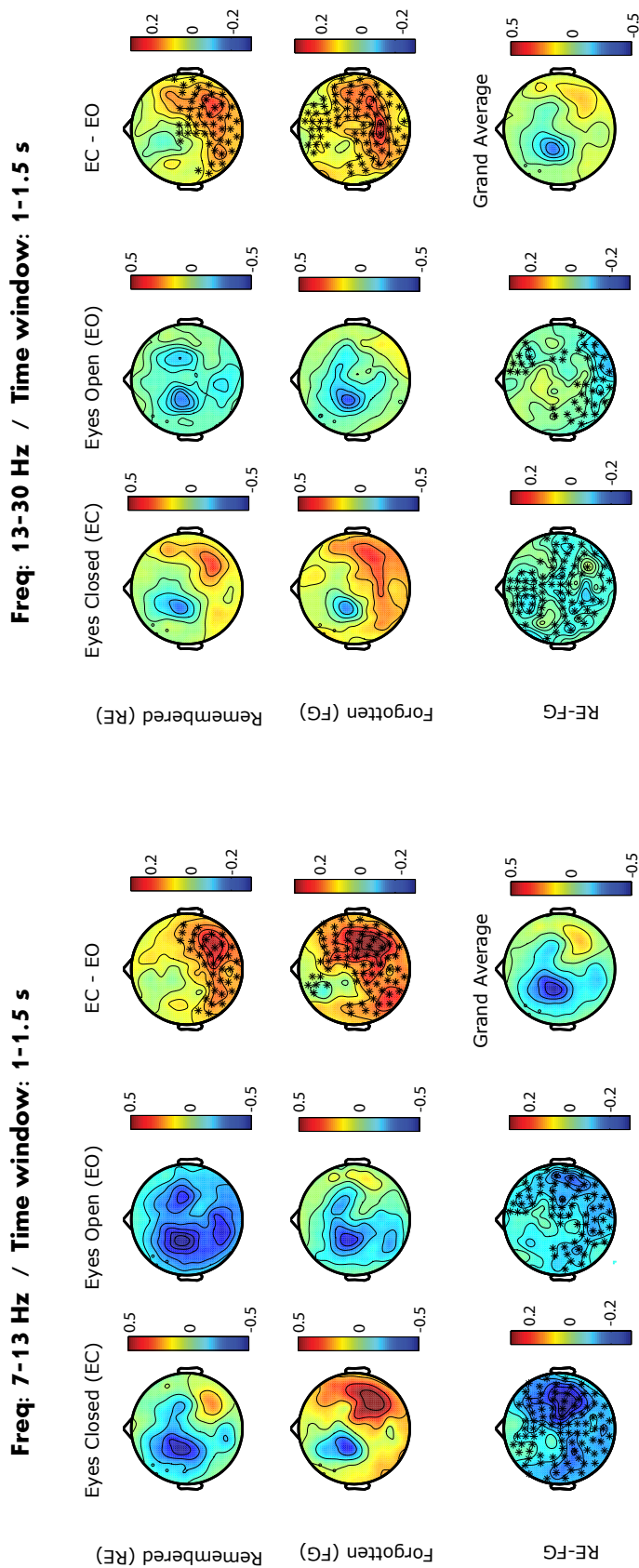
5.7. irudia: Berreskuratze faseko oszilazio analisia. Eskema 5.3. irudiaren eskema bera da. (c),(f),(g) eta (h) grafikoek soilik estatistikak babestutako denbora-frekuentzia leihoak erakusten dituzte.

Unrestricted Analysis Power Topography



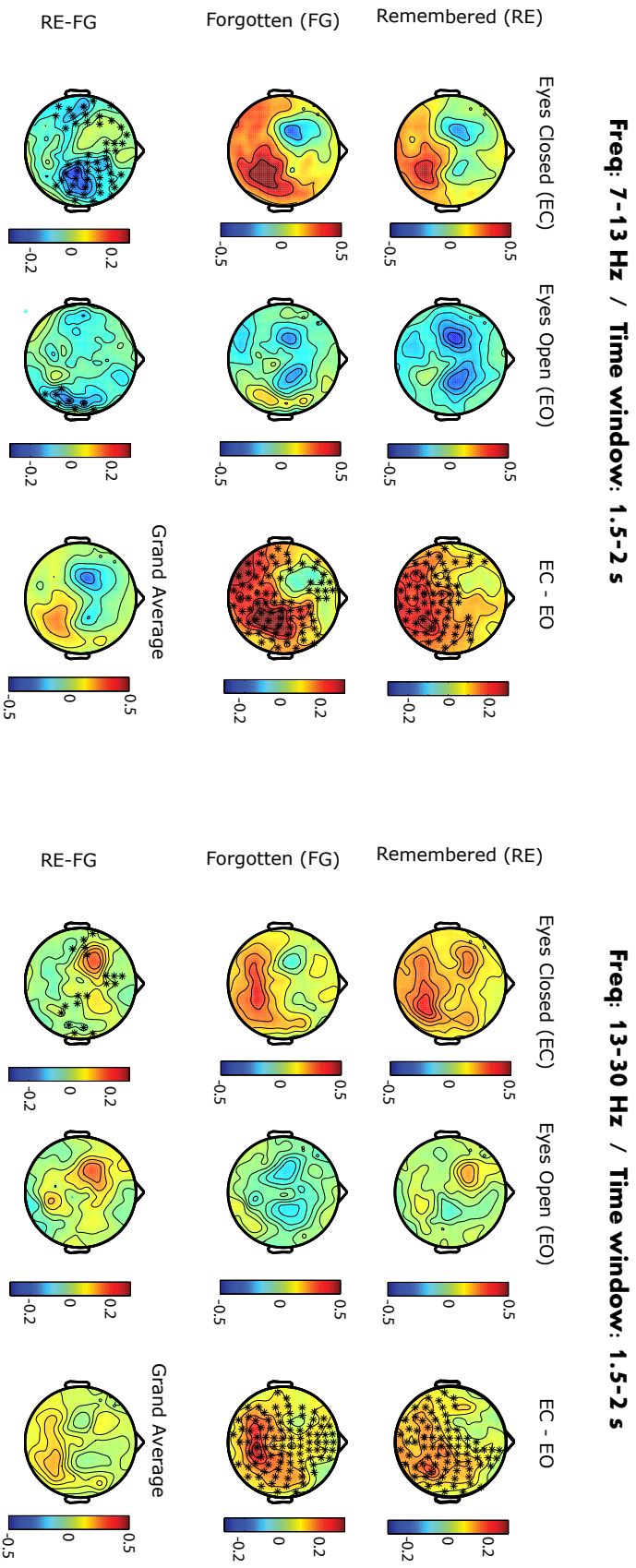
5.8. irudia: Alfa bandaren (7-13 Hz) eta beta bandaren (13-30 Hz) topografiak 0.5 eta 1 s artean. Ezkerreko panelak (a) alfa bandaren topografia irudikatzen du. Eskuineko panelak (b) beta bandarena. Irudi bakoitzean, lehenengo lerroak gogoratutako hitzen potentzia aldatetarako erakusten ditu, eta bigarrenak ahaztutako hitzenak. Lehenengo zutabeak begi itxien potentzia aldatetarako irudikatzen ditu, eta bigarrenak begi irekienak. Hirugarren lerro eta zutabeak ondoko bi egoeren diferentziak irudikatzen ditu. Eta behe-eskuinean dagoen graffkoak batezbesteko orokorra irudikatzen du.

Unrestricted Analysis Power Topography



5.9. irudia: Alfa bandaren (7-13 Hz) eta beta bandaren (13-30 Hz) topografiak 1 eta 1.5 s artean. 5.8 irudiaren eskema bera jarraitzen du.

Unrestricted Analysis Power Topography



5.10. irudia: Alfa bandaren (7-13 Hz) eta beta bandaren (13-30 Hz) topografiak 1.5 eta 2 s artean. 5.8 irudiaren eskema bera jarraitzen du.

badentan topatzen da, ERS handiagoa agertzen delarik begi itxiekin begi irekiekin baino. Efektua nagusiki atzealdeko sensore eta eskuin sensore parietaletan ageri da (ikus 5.8, 5.9 and 5.10, c eta f irudiak).

A priori analisisiko eskema berdina jarraituz, analisi estatistikoak burutu ziren interakzioak neurtzeko. Mugatutako analisiaren antzera, emaitzek ez dute mulko esanguratsurik erakusten ($\text{abs}(\text{clusterstat}) < 259$; $p > 0.71$).

Iturri analisia

5.11, 5.12 eta 5.13 irudiek iturri mailan egindako potentzia analisisien emaitzak irudikatzen dituzte.

Hiru denbora leihotako batezbesteko orokorrekin burmuin osoan sakabanatutako alfa (7-13Hz) desinkronizaizoa erakusten dute, nahiz eta desinkronizazio nagusia ezker motore eremutan ageri den.

Egoera ezberdinak konparatuta, emaitzak sensore mailan topatutako efektuekin bat egiten dute. Lehenengo denbora leihoan (0.5-1 s) analisi estatistikoak soilik begi irekiekin gogoratutako eta ahaztutako hitzen arteko ezberdintasuna babesten du. Mulkoa eskuin atzealdeko eremuan eta behe lobulu tenporal eta okzipitalean kokatzen da ($\text{clusterstat} = -684.17$; $p\text{value} = 0.035$).

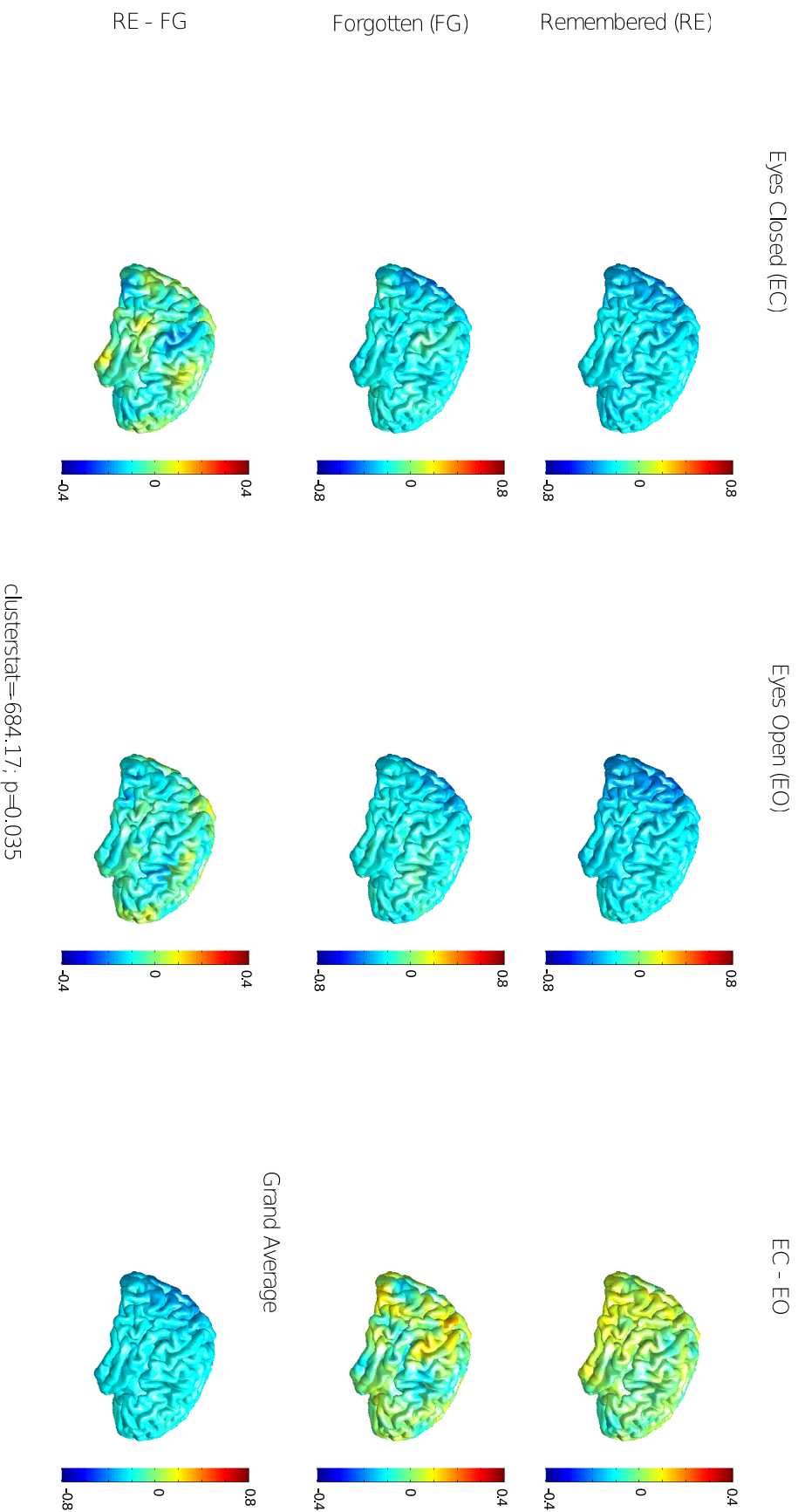
Bigarren denbora leihoan (1 - 1.5 s) analisi estatistikoak bi efektuak jasotzen ditu: begi itxiena eta elementu motarena (see Figure 5.12). Begi irekiekin gogoratutako hitzek, ahaztutako hitzek baino ERD handiagoa erakusten dute ezker IFGan, atzealdeko STGan eta zirkunboluzio angularrean ($\text{clusterstat} = -889.23$; $p\text{value} = 0.017$). Begi itxiekin, gogoratutako hitzek, ahaztutakoek baino alfa ERD handiagoa eskuin lobulu parietal eta frontaletan ($\text{clusterstat} = -1155.2$; $p\text{value} = 0.008$). Gogoratutako hitzetan, begi itxiek alfa ERS handiagoa erakusten dute eremu okzipital eta atzealdeko lobulu parietaletan ($\text{clusterstat} = 645.15$; $p\text{value} = 0.049$).

Hirugarren denbora leihoan (1.5 - 2 s) analisi estatistikoek begi-itxien efektua erakusten dute (ikus 5.13 irudia). Gogoratutako eta ahaztutako hitzetan begi itxiek, begi irekiet baino alfa ERS handiagoa erakusten dute eremu okzipital eta atzealdeko-parietaletan ($\text{clusterstat} = 2931.1$; $p\text{value} < 0.001$ and $\text{clusterstat} = 1184.5$; $p\text{value} = 0.005$ hurrenez hurren).

Aurreko bi analisisetan bezala, analisi estatistikoak burutu ziren interakzioak neurtzeko. Emaitzek ez zuten mulko esanguratsurik azaldu ($\text{abs}(\text{clusterstat}) < 222.94$; $p > 0.18$).

Source-level Power Analysis

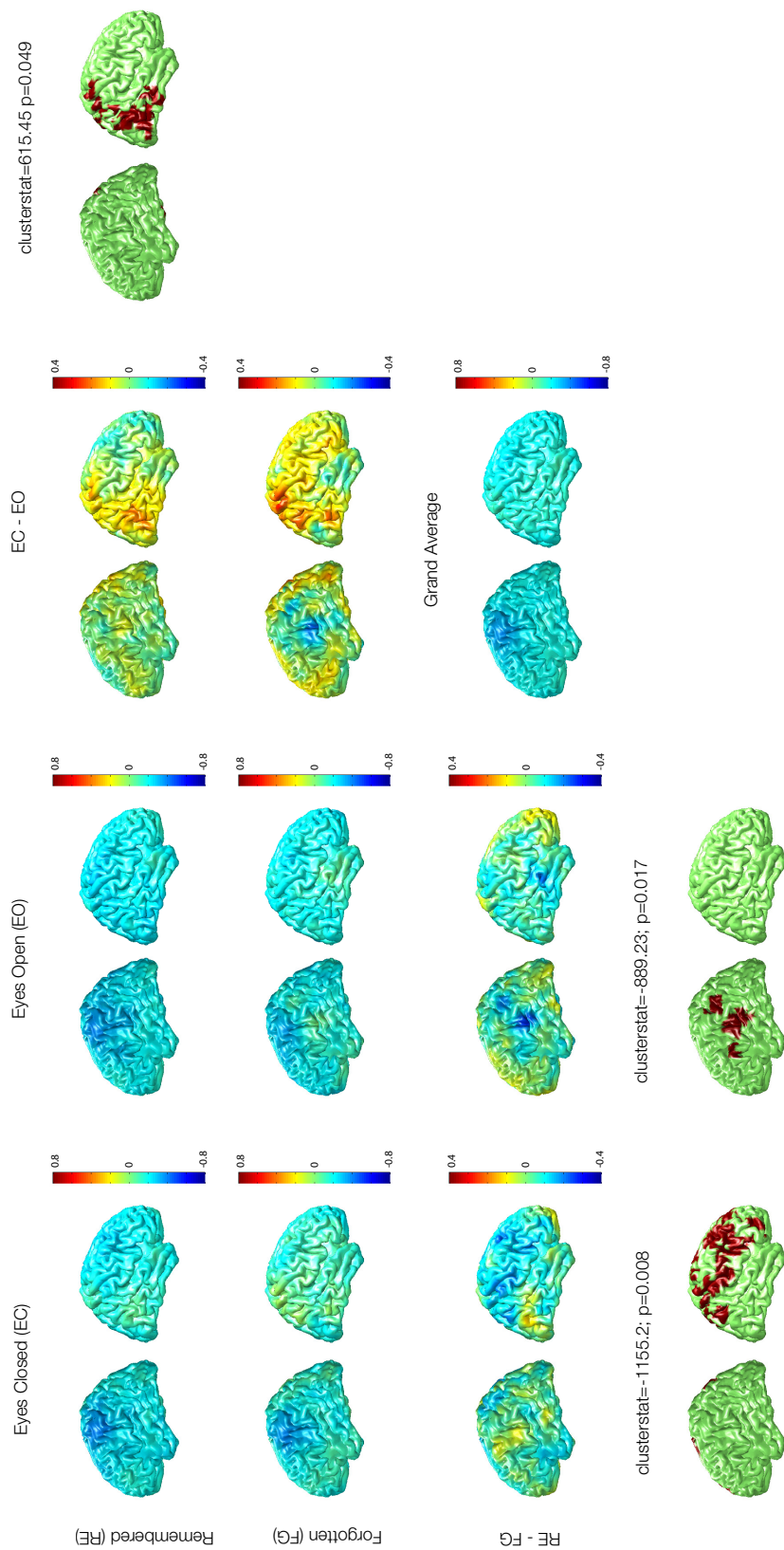
Freq: 7 - 13 Hz / Time window: 0-0.5 s



5.11. irudia: Alfa bandaren (7-13 Hz) iturri berreraikitzea 0.5 eta 1 s artean. Laugarren lerro eta zutabeek egoeren arteko diferentzia estatistikoak erakusten dituzten mulkoen kokalekuak irudikatzen dituzte. Eskema 5.8. irudiaren eskema bera da.

Source-level Power Analysis

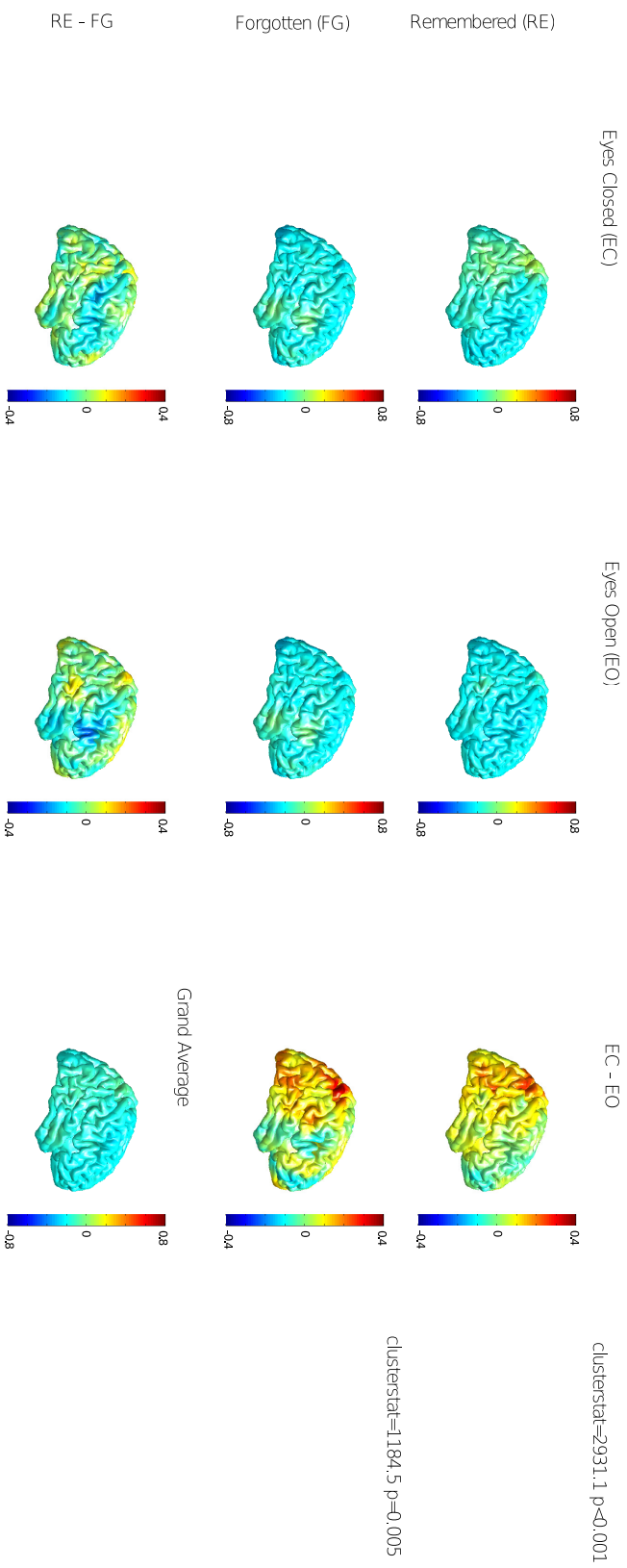
Freq: 7- 13 Hz / Time window: 1-1.5 s



5.12. irudia: Alfa bandaren (7-13 Hz) iturri berreraikitzea 1 eta 1.5 s artean. Laugarren lerro eta zutabeek egoeren arteko diferentzia estatistikoak erakusten dituzten mulkoen kokalekuak irudikatzen dituzte. Eskema 5.8. irudiaren eskema bera da.

Source-level Power Analysis

Freq: 7 - 13 Hz / Time window: 1.5-2 s



5.13. irudia: Alfa bandaren (7-13 Hz) iturri berreraikitzea 1.5 eta 2 s artean. Laugarren lerro eta zutabeek egoeren arteko diferentzia estatistikoak erakusten dituzten mulkoen kokalekuak irudikatzen dituzte. Eskema 5.8. irudiaren eskema bera da.

5.5 Eztabaida

Esperimentu honetan, partaideek begi irekiekin eta begi itxiek antzemate oroimen ariketa batean entzundako hitzak klasifikatu zituzten. MEG seinalearen oszilazio potentzian egindako analisi ezberdinek oroimen arrakastatsua, estimulua aurkeztu eta segundu erdira gertatutako alfa bandaren desinkronizazio handigoarekin erlazionatuta dagoela erakutsi zuten. Bestalde, begi itxiera desinkronizazio horren ondorengo denbora leihotako alfa eta beta sinkronizazioarekin erlazionatu zen. Begi itxiek ez zituzten oroimen ariketako erantzun zuzenenen kopuruak modulatu. Halaber, alfa ERD eta alfa/beta ERS artean ez zen interakziorik topatu. Gainera, begi itxiek atzealdeko sensoreetan eragindako alfa potentzia igoera klasikoa topatu zen separatuta grabatu zen atsedeen bloke batean.

Mugatutako analisia, alfa banda begi itxierarengatik eta elementu motarengatik modulatu izango zela azaltzen duen hipotesia frogatzeko erabili zen, eta bide batez, bi modulazio horien arteko interakzio posiblea neurtzeko. Mugatu gabeko analisia, mugatutako analisisian topatutako emaitzak frekuentzia mugak sortutako joera batek sortuak ziren edo ez neurtzeko erabili zen. Bi analisiak konparatzerakoan, mugatutako analisisian elementu motak (gogoratutakoak eta ahaztutakoak) eragindako ERD modulazioak; mugatu gabeko analisisian ere topatu ziren, gainera, denbora leihotako, sensore eta frekuentzia beretan. Bestalde, mugatu gabeko analisia burutzean begien itxiera efektua frekuentzian zabaltzen dela ikusi zen (beta banda hartzen duelarik). Ondorioz, bi analisisien emaitzak bateratzean, bi analisisietan topatutako alfa ERD modulazioak alfa jaitziera bera bezala tratatzen dira, eta begi itxiek sortutako ERSa alfa eta beta banden potentzia igoera bateratu bezala tratatzen da. Horrengatik, bi analisisietako emaitzak efektu berdinak isladatzen dituztela interpretatzen da, eta ondorioz, elkarrekin eztabaidatzen dira.

Oroimen ariketa bateko berreskuratze fasean, partaideek estimulua zaharra edo berria bezala klasifikatu behar dutenean, aurretiko ikerketek estimuluari erantzunez alfa desinkronizazio bat gertatzen dela erakutsi dute (Klimesch, 1999; Schack and Klimesch, 2002; Klimesch et al., 2003). Gainera errendimendu hobea alfa ERD handiagoekin lotu izan da (Klimesch et al., 1997; Klimesch, 1999; Doppelmayr et al., 2005; Hanslmayr et al., 2005). Kapitulu honetan aurkeztutako esperimenteraren datuek aurreikusitako oroimen efektua erakutsi dute: gogoratutako hitzetan alfa ERDa handiagoa zen ahaztutako hitzetan baino. Hala ere, aurreko ikerketek alfa efektua atzealdeko sensoreetan kokatzen zuten, eta esperimentu honetan MEG sensore tenporaletan (gradiometro planarrak) ere efektua ikusi zitekeen. Iturri analisiak, begiak irekiak zeudenean, efektua ezker goi-lobulu tenporalean eta IFG eremutan kokatu zuten. Begiak itxita zeudenean, efektua eskuin lobulu parietal eta

frontaletan kokatu zen. Aurreko ikerketen eta hemen aurkeztutako esperimentuaren kokaleku diferentzia EEG eta MEG tekniken sentikortasun ezberdinek azaldu dezakete, baina badira beste azalpen batzuk ere.

Aurreko ikerketek estimulu bisualak erabili dituzten bitartean, hemen aurkeztutako esperimentuak estimulu auditiboak erabili ditu, begi itxiek oroimen berreskuratzean duen efektua aztertu ahal izateko. Kontuan izan Krausek estimulu auditiboak erabili zituela ere (Krause et al., 1996) eta nahiz eta estimuluei erantzunez alfa ERDa topatu zuen, portaerak ez zuen alfa ERDa modulatu. Klimesch-en arabera Kraus eta lagunek ez zuten oroimen efekturik topatu, estimulu auditiboek tau erritmoa modulatu zuelako (Klimesch, 1999). Klimeschek proposatu zuen EEG teknika ez dela egokiena tau erritmoa jasotzeko (Klimesch, 1999), eta gainera, MEG teknika erabili izan denean oroimen ariketa auditiboetan sensore tenporaletan tau erritmoaren modulazioak ikusi egin direla azpimarratu zuen (Kaufman et al., 1992). Honetaz gain, ikerketa berriek alfa ERDa arreta jarri beharreko estimulu motaren arabera, modalitate-horren eremu sentsozialean (eremu tenporalak estimulu auditiboentzat eta atzealdeko eremuak estimulu bisualentzat) topatzen dala erakutsi dute (Jiang et al., 2015).

Esperimentu honek estimulu auditiboak erabili izanak eta efektuak nagusiki eremu tenporaletan topatu izanak, emaitzek tau erritmoaren modulazioa erakusten ari direla adierazten dute. Kontuan izan, begi irekiekin oroimen efektua hizkuntza sarearen parte diren eremuetan kokatu zela.

Zein da 10-Hz inguruan oszilatzen duten erritmoei izen ezberdina jartzearen eragin teorikoa? Erritmo baten modulazioaren funtzioa (e.g., ERS, ERD), frekuentziaz gain, erritmo hori sortu duen burmuin sarearen menpe egon daiteke. Atzealdeko eremutan ageri den 10 Hz-ko erritmo baten modulazioa, eta eremu tenporaletan ageri den 10 Hz-ko erritmo baten modulazio berak funtzio ezberdinak izatea, nahiz eta modulazioaren sorrera fisiologikoa oso antzekoa izan daiteken bi egoeratan.

Lan honetan begi itxierak eragindako bi modulazio topatu ziren. Lehenengoa, atsedean blokean begiak ixtean gertatzen den alfa handitze 'klasikoa' da. Alfa potentzia igoera hau, magnitude txikiagoarekin berreskuratze fasean ageri da ere (ikus 5.2 irudia). Begi itxiek eragindako bigarren modulazioa, estimuluari erantzunez sorrarazitako-potentzia analisisan ikusitako alfa eta beta potentzia igoera da. Bi frekuentzia bandatan, sensore okzipitaletan eta parieto-tenporaletan, ERS efektua handiagoa zen begi itxiekin begi irekiekin baino. Alfa bandako begi itxien efektua, bai gogoratutako eta bai ahaztutako hitzentzat, eremu okzipitaletan eta atzealdeko eremu parietaletan kokatu zen iturri analisisa erabiliz. Askotan ikusi izan den alfa potentzia absolutuaren handiagotzearengatik, begi itxiek eragindako alfa modulazioa aurreikus

daiteken arren, begi itxiek sorrarazitako-potentzian eragiten duten modulazioa ez da azaltzen literaturan.

Metodologiak eragindako arazo izan daitekeena azpimarrtau beharra dago: begi itxien eta begi irekien arteko konparaketak, estimulu ondorengo modulazioetaz gain erreferentzia base potentzia ezberdinak nahasten ditu. Erreferentzia basearen potentzia ezberdintasunak potentzia erlatiboaren interpretazioa zailtzen du, ambiguitasun bat ageri delako: ikusitako ezberdintasunak erreferentzia eta leiho aktiboaren arteko potentzia diferentzia batek eraginda edota soilik erreferentzia basean potentzia absolutuen diferentziak eraginda izan daitezke. Hala ere, begi itxietan topatutako beta-ERSa, potentzia absolutu handiagoa duen erreferentzia base batekiko (e.g., 5.2 irudia), aldaketa erlatiboa handiagoa erakusten du. Honek, begi itxiekin begi irekiekin baino potentzia aldaketa absolutu handiagoa dagoela adierazten du.

ERS efektu honen interpretazio posible bat, begi itxiek alfa bandan eragindako efektuaren espantsio bat izatea da. Hau da, alfa bandak potentzia handiagotzen duenean gailur espektrala zabaldu egiten da eta ondoko frekuentziak hartzen ditu (theta eta beta). Atsedean blokeetan begi itxiek frekuentzia ezberdinetan eragiten dituzten efektuak ikertzean, antzeko efektu bat topatu zuten beta frekuentzia bandan: atzealdeko EEG sensore eta eskuineko sensore parietaletan, begi itxiek beta bandako potentzia handiagotzen zuten (Barry et al., 2007).

Bestalde, beta-ERSa mugimendu ondorengo errebote bat bezala interpretatu daiteke (Pfurtscheller et al., 1996, 1998). Aktibitate motore baten ondoren, beta bandako potentziak ERS bat erakutsi ohi du. Testuinguru honetan, beta-ERSaren modulazioa egoera ezberdinen diferentzia motoreari edo somatosensoreari lotuta egongo litzateke. Faktore ezberdinek beta errebotea modulatu dezaketela erakutsi dute hainbat ikerketek, adibidez, mugimendu baten egindako indarrak (Fry et al., 2016) edota ikusitako mugimendu baten zuzentasunak (Koelewijn et al., 2008). Guk dakigula, ez dago beta errebotearen eta begi itxien arteko lotura aztertzen duen ikerketarik. Hala ere, behatz mugimenduak begi irekiekin (non mugimendua ikusi daitekeen) edo begi itxiekin (non mugimendua ezin den ikusi) ezberdinak izan ditzakete. Diferentzia honek, beta errebotean agertutako ezberdintasunak azaldu ditzake. Nahiz eta azalpen hau guztiz espekulatiboa den, etorkizunean erraz diseinatu daiteke begi irekiek eta itxiek behatz mugimenduen oszilazioetan eragiten dituen aldaketak neurtzeko esperimentu bat. Azalpen honen hutsune nagusia, beta-ERS modulazioak atzealdeko sensoreetan (eta ez motor eremu inguruko sensoreetan) topatu zela da. Gainera beta igoeraren topografia begi itxiek eragindako alfa igoeraren topografiaren, eta baita ere Barry et al. (2007)-k aurkeztutako emaitzen,

oso antzekoa da. Hori dela eta, lan honetan topatutako beta-ERS modulazioa, begi itxiek eragindako alfa-modulazioaren espantsio bat dela proposatzen da.

Nola eragiten du begi itxierak alfan (edo taun)? Datu hauen ezaugarri deigarriena da alfa-tau bandako erantzunek ez dutela ERD handiagoa erakusten begi itxiekin, baizik eta alfa-beta ERSaren modulazio berantiar bat. Begi itxiek alfa modulazio bat eragitea espero daitekeen arren, garrantzitsua da azpimarratzea neurtutako sorrarazitako-potentzia hitz auditibo baten antzemateari eta ulermenari lotutako erantzuna dela. Atsedean blokeko potentzia absolutuan ikusitako aldaketen aurka, hemen, frekuentzia banda ezberdinek hitz bati erantzunez erakusten dituzten dinamikak ageri dira, eta hemen, badirudi, begi itxiek ERS berantiarra modulatu dutela. Gainera begien itxierak ez zuen ariketako errendimenduan ez onurarik ez galerarik eragin. Honek, paradigma konkretu honetan oroimen efektuak tau erritmoa modulatu duela eta begien itxierak atzealdeko alfa-beta erritmoak modulatu dituztela eta bien artean interakziorik ez dagoenaren hipotesia berresten laguntzen du. Bestalde, iturri analisiak erakusten du begi itxierak gogoratutako eta ahaztutako hitzen efektuaren kokalekua aldatzen duela: begi irekiekin efektua hizkuntza sarean kokatzen da eta begi itxiekin eskuineko lobulu parietal eta frontalean. Hala ere, interakzioak estatistikoki neurtuak izan zirenean ez zen interakzio esanguratsurik topatu.

Hemen aurkeztutako esperimenduaren emaitzek modalitate espezifiko hobekuntza hipotesiarekin bat egiten dute. Hipotesi honen arabera, begiak itxerakoan interferentzia bisualak murrizteak irudikapena errazten du eta oroimen bisuala hobetzen du, baina ez ditu beste modalitateko oroimen berreskuratzeak hobetzen (Vredeveldt et al., 2011, 2012). Hemen arukeztutako esperimenduan, partaideek ikasi beharreko materiala modalitate linguistikokoa zen. Berreskuratze fasean material honen gogoratzea, hizkuntza sarean oinarritu daiteke: bi hemisferioetako mintzamen antzemate eremutan eta ezkerreko eremu perisilbianoan. Egindako analisi oszilatarioaren arabera, begi itxien bitartez atzealdeko alfa modulatuak ez du hizkuntza sarearen errendimendua zuzenki modulatu, eta ondorioz, oroimen ariketaren errendimenduan ez zen ez onurarik ez galerarik topatu.

Kontuan hartu behar da azalpen hau egoera ortogonalak erabiliz neurtu daitekeela. Hala ere, belarri itxiera eta begi itxiekin ikusmena neurtuko dituen diseinu bat irudikatzea ez da erraza. Horregatik, burmuineko erritmoen independentzia eta interakzioak neurtzeko ikerketa gehiago egin behar direla proposatzen da, hauen emaitzak modalitate espezifiko hobekuntza eta karga murrizteak prozesu kognitibo ezberdinetan nola eragiten duten ulertzeko erabili.

5.6 Laburpena

Esperimentu honetan aurreikusitako oroimen efektua topatu zen: gogoratutako hitzek, ahaztutako hitzekin alderatuta, alfa ERD handiagoa eragiten dute. Efektu hau, atzealdeko sensoreetan aurkitu ordez, nagusiki eremu tenporaletan topatu zen. Iturri analisiak efektua hizkuntza sarean eta eskuineko lobulu parietal eta frontaletan kokatu zuen. Eraitza hauek oroimen efektua tau erritmoa modulatzeko duenaren eta begi itxierak atzealdeko alfa modulatzeko duenaren adierazgarri dira. Bi modulazio arteko interakzio faltak, tau eta alfa erritmoak erritmo independente bezala tratatu behar direla adierazi lezake. Eta honek, testuinguru konkretu honetan begi itxierak oroimen errendimendua zergatik ez duen modulatu azalduko luke. Datuek, analisiak denbora leihotxiki batean zentratzean, oszilazio aldaketak neurtzea erraza dela ere erakusten dute. Honek azalduko luke zergatik 4. kapituluko esperimentuan ez zen oszilazioen modulaziorik topatu.

III. Atala

Eztabaida eta azken oharrak

6. Kapituluia

Eztabaida orokorra eta laburpena

Tesi honen helburu nagusia burmuin helduetan hizkuntzarekin lotutako epe-motzeko aldaketak neurtzea zen. Aurreko ikerketek nagusiki luzetarako eta zehar-sekzio diseinuak erabili dituzte, eta ondorioz, finkatuta dauden arauen burmuin erantzunak neurtu dituzte. Bestalde, momentuko eta laborategiko trebakuntza erabili dituzten ikerketek, eta ondorioz epe-motzeko aldaketak neurtu dituztenak, EEG teknika erabili zuten eta ez dituzte efektuen adierazle anatomikoak azaltzen. Epe-motzeko eta epe-luzeko ikasketak aldaketa plastiko ezberdinak eragiten dituzte (Rossini and Melgari, 2011), beraz, tesi honetako MEGean egindako esperimentuek aurkezten dituzten adierazle anatomikoak epe-motzeko ikasketan gertatzen diren aldaketa plastikoak hobeto ulertzeko baliagarriak dira. Bi esperimentutan hizkuntza naturalen azpimultzoak (hizkuntza miniaturizatuak) erabili ziren epe-motzeko aldaketak aztertzeko. Hizkuntza miniaturizatuak hizkuntzarekin lotutako aldaketak, ikastaro trinkoen beharrik gabe, ikustea ahalbidetzen dutela hipotetizatu zen. Hirugarren esperimentua partaideen ama-hizkuntzan burututako oroimen esperimentu bat da, oroimenaren funtzio fisiologikoak, eta bereziki oroimen berreskuratzean oszolazioak duen funtzioa hobetu ulertzeko helburuarekin egin zena.

6.1 Emaitzen laburpena

Lehenengo esperimentuan, kontrol-urratzeak era kontzientean antzemateko ariketa bat erabiliz gramatika ikasketa aztertu zen. Honela, MEG teknikak burmuinaren aktibitatea denbora eskala oso motzean jaso ahal izan zuen. Ikasketaren (trebakuntzaren) aurretik, bitartean eta ondoren MEG seinaleak eta ariketaren erantzunak jaso ziren eta ama-hizkuntzan (H1) burututako ariketa berdinarekin alderatu ziren. Emaitzek erakutsi zuten, trebakuntza aurretik partaideek ezin zituztela izen sintagmak zuzenki klasifikatu. Lehenengo trebakuntza bloketik

aurrera ordea, erantzun zuzenen kopurua goi-mugan zegoen eta errendimendu hau orokortze proban mantendu zuten. Urraketa prozesatzen duen burmuin sarea trebakuntzarekin aldatzen joan zen. Lehenengo trebakuntza blokean, sarea eskuin lobulu fronto-parietalean eta tenporalean kokatu zen. Azkeneko trebakuntza blokean eta orokortze-proban, sarea ezker lobulu tenporalean eta behe zirkunboluzio frontalean (IFG) kokatu zen, azken hau, H1an parte hartzen duen hizkuntza sarearen oso antzekoa delarik.

Bigarren esperimentuan, esaldi-entzumen ariketa bat erabiliz hizkuntza ikasketa aztertu zen. Partaideek beraien ama-hizkuntzan eta hizkuntza ezezagun batean esaldiak entzun zituzten MEG seinaleak grabatzen ziren bitartean. Ariketa bera hizkuntza-ezezagunean egindako trebakuntza aurretik eta ondoren burutu zen. Esperimentu honetan esaldi entzumenean sortutako oszilazio erantzunak aztertu ziren. Oszilazio potentzia aldaketa hizkuntza sarean topatu ziren bai ama-hizkuntza entzutean bai hizkuntza ezezaguna entzutean, nahiz eta potentzia aldaketak handiagoak izan ziren hizkuntza ezezagunean (efektu hau bloke ordenarekin nahastuta egon daiteke). Hizkuntza ikasketak oszilazioak modulatzeko dituela erakusten duten ebidentzia indartsurik ez zen topatu.

Hirugarren esperimentuan, ama-hizkuntzan ematen den oroimen berreskuraketa aztertu zen, oroimen berreskuratzean parte hartzen duen aktibitate oszilatarioa hobeto ulertzeko. Partaideek begiak itxita zituztenean, begiak irekita zituztenean baino hitz gehiago antzemango zituztela hipotetizatu zen. Pentsatutakoaren aurka, begi itxierak ez zuen ariketaren errendimendua modulatu. MEG seinaleei dagokienez, begi itxierak aurreikusitako alfa igoera eragin zuen sensore okzipito-parietaletan. Hala ere, oroimenak eragindako alfa modulazioak sensore tenporaletan topatu zen (tau erritmoa). Gainera ez zen alfa eta tau erritmoen arteko interakziorik topatu.

6.2 Nola modulatzeko dira burmuin sareak epe-motzeko ikasketarekin?

Aurretik egin diren ikerketek, ikasketa aldaketak aztertzeke, ERP neurgailuak portaera neurgailuak baino sentikorragoak izan daitezkeela erakutsi dute (Kotz and Elston-Güttler, 2004; Mueller, 2005). Honekin bat eginez, 3 kapituluko esperimentuan portaera emaitzak blokeetan zehar antzeko mantendu diren arren, ERF modulazioak aldatu egin ziren. Gainera tesi honetan azaldutako esperimentuek burmuinaren aldaketa funtzional ezberdinak antzeman zituzten. Alde batetik, 3 kapituluko emaitzek ariketa burutzeko parte hartzen duten burmuin eremuak

trebakuntzarekin aldatzen direla erakutsi zuen. Bestalde, 4 eta 5 kapituluetakoa esperimientuek burmuin eremu berdinetan gertatutako oszilazio aldaketak antzeman zituzten.

3 kapituluko esperimientuan, adibidez, lehenengo trebakuntza blokean gramatikalitate efektua eskuineko lobulu fronto-parietaletan eta tenporalean kokatua zegoen. Eskuin eremu frontala akats-sintaktikoetara mugatzen ez den akats antzemateekin lotua izan da lehenagotik (Indefrey et al., 2001). Gainera, HERA modeloan oinarrituta (Habib et al., 2003), eskuin kortex aurrefrontala oroimen berreskuratzearekin lotua dago. Hala ere, trebakuntza minutu batzuen ondoren, bigarren trebakuntza blokean gramatikalitate efektua ezkerreko lobulu parietal eta tenporaletan kokatu zen. Hirugarren blokean efektua ezker lobulu tenporalean kokatu zen. Azken bi blokeetan efektu nagusia hizkuntza sarean kokatzeak, H2ko oroimen berriak dagoeneko lexikoa eta gramatika prozesatzen duten eremuetan sortu eta txertatzen direla adierazi lezake; eta ez beste prozesu kognitiboetaz arduratzen diren eremu baztertuetan. Sare aldaketa hauek 'gramatikalizazio' trantsizio baten adierazle bezala ulertu daitezke, non ikasitako arauak ikaslearen hizkuntza-prozesamenduko denbora-errealean finkatzen diren (McLaughlin et al., 2010).

Nahiz eta 3 kapituluko emaitzak hizkuntza-ikasketako epe-mozteko beste ikerketetako emaitzekin bat datozen (Mueller et al., 2008, 2007, 2005; Davidson, 2010; Davidson and Indefrey, 2009a), hasiera batean epe-luzeagoko beste ikerketa batzuekin kontraesanean daude. Esperimientu honetako emaitzek hizkuntzaren trebetasun berri batek burmuin sareak azkar moldatzen direla erakusten dute, eta minutu gutxi batzuen ostean trebetasun hori H1 sarearen antza duen sare batean oinarritzen dela. Honen aurka, hizkuntza ikastaro ofizialetako lehen urteko ikasleek H2n erakusten dituzten gramatikalitate efektu patroiak eta H1n erakusten dituztenak ezberdinak direla erakutsi dute luzetarako ikerketek (McLaughlin et al., 2010). Epe motzeko ikasketa ikerketetan partaideek hizkuntzen frakzio txikiak praktikatzeko dituztela eta frakzio beretan aztertuak direla izan daiteke azalpen posible bat. Alabaina, luzetarako ikerketetako partaideek hizkuntza baten ezaugarri ezberdinak ikasten dituzte, baina frakzio txiki batean dira aztertuak. Gerta daiteke aztertuak diren frakzio horiek oraindik gramatikalizatu gabe egotea (McLaughlin et al., 2010). Beste azalpen posible bat, ikasketa intentsiboan gertatzen diren burmuin aldaketak, praktika mantendu ezean, epe luzera galtzen direla izan daiteke. Honetaz gain, esperimientu honetako emaitzek, ERF efektuen denbora eta forma antzekoak direnean ere iturri analisia sensore mailan ikusten ez diren aldaketetara sentikorra dela erakusten dute. Iturri analisiari esker, ERFei lotutako burmuin sarean aldaketak antzeman ziren. Hau dela eta, EEGrekin alderatuz MEG teknikak duen zehaztasun

espazial hobetuak (Baillet, 2017), posizio hobeago baten uzten du hizkuntzarekin lotutako burmuin plastikotasuna aztertzeko.

4 kapituluan azaldutako esperimentuari dagokionez, ez da ikasketak eragindako oszilazio aldaketan ebidentzia indartsurik topatu. Hala ere, honek ez du ezinbestean aldaketa plastikorik ez dela egon adierazten. Izan daiteke datuetan burututako analisisiek plastikotasun hori ez neurtu izana. Lan honetan aztertutako frekuentzia banden potentziek esaldi osoen erantzuna adierazten du, mintzamenaren entzumenean gertatzen diren funtzio kognitibo ezberdinak jasotzen dituelarik (e.g., Friederici, 2011). Analisiak denbora leiho txiki batean zentratzean, agian oszilazio hauetan gertatutako aldaketak neurtu daitezke, 5 kapituluan ikusi den bezala. Bestalde, izandako trebakuntza saioa oszilazioetan aldaketak eragiteko nahikoa ez izatea gerta daiteke. 3 esperimentuak jabetutako jakintzaren txertatze azkarra erakusten duen bitartean, hau ez da gertatzen 4. kapituluan.

Hasiera batean, hau ikasketak sintaktikoa semantikoa baino zailagoa dela esaten duten aurreko ikerketekin kontraesanean dagoenaren irudimena eman dezake (Sanders et al., 2008; Birdsong, 2006). Alabaina, tesi honetako esperimentuan ikasitako hiztegia esaldietan txertatuta dago. Esaldien prozesamenduak prozesu kognitibo ugari barneratzen ditu (e.g., mintzamenaren segmentazioa). Honek, MEG datuetan burmuin aldaketak ikusteko esaldi prozesamenduaren trebakuntzak denbora gehiago behar izatea azaldu lezake. Hirugarren aukera bat, trebakuntza bitartean burmuin aldaketak gertatu baina hauek MEG saiorarte iraun ez izana da. 3 kapituluan zaldu bezala, epe-motzean gertatutako burmuin aldaketen iraunkortasuna ikertu gabe jarraitzen du.

6.3 Hizkuntza ikasketaren hasieran hizkuntza sareak parte hartzen al du?

H1 eta H2 prozesamendu sareek zenbateko bat-etortzea duten eta ea H2 prozesamenduak H1 hizkuntza sarean oinarritzen den, bigarren hizkuntza jabetzaren alorrean behin eta berriz errepikatzen diren ikerketa galderak dira (ikus Indefrey, 2006, -k egindako fMRI ikerketen laburpena). Aurreko ikerketetan, H2 ikasleak H1 ama-hiztunekin konparatuak izan dira (ikus Caffarra et al., 2015, -k egindako EEG ikerketen laburpena). Tesi honetan ordea, partaide talde berdina beraien ama-hizkuntzan (H1) eta ikasi berri zuten hizkuntzan (H2) aztertu ziren.

Nahiz eta 3 kapituluan ez dagoen H1 eta beste blokeen arteko konparaketa kuantitatibo zuzenik, bi hizkuntzetan erabilitako burmuin eremuen konparaketa

kualitatiboa azaltzen da jarraian. Bigarren trebakuntza bloketik aurrera, urraketa eta kontrol sintagmen arteko ezberdintasun gordina ezkerreko kortex tenporalean eta behe-frontalean kokatzen da. Ereku hauek literaturako modelo ezberdinek proposatutako hizkuntza-prozesamendu sarearekin bat datoz (Hagoort, 2016; Friederici, 2011). Hala ere, analisi estatistikoek soilik gainjartze partziala babesten dute, eta eremuak bloketik blokerara aldatzen dira. Gainjartze partzial hau MEGean gauzatutako beste ikerketa batekin bat dator (Davidson and Indefrey, 2009b). Ikerketa honetan urratze efektuak hizkuntza sarean kokatu ziren, baina proba saio bakoitzean hizkuntza sareko eremu ezberdin batean kokatu zen efektua.

Bestalde, 4 kapitulu burmuin osoko analisiak hizkuntzaren efektua eremu frontaletan kokatu zuen theta bandarentzat eta bi hemisferioetako eremu tenporaletan alfa bandarentzat. Patroi hauek H1 prozesatzerakoan agertzen diren patroiekin bat egiten dute (Lam et al., 2016). Lan honetan aurkeztutako emaitzek, bigarren hizkuntzan ama-hizkuntzan baino oszilazio aldaketa handiagoak erakusten dituzte. Alfa desinkronizazioak informazio prozesamendu egoera isladatzen duela, eta alfa sinkronizazioak inhibizio egoera isladatzen duela proposatu izan da (Klimesch et al., 2007). Honetan oinarrituta, esperimentu honetako patroiek eremu tenporalek H2an mintzamen prozesamendurako informazio prozesamendu handiagoa behar dutela, eta beste eremuek H1an baino inhibizio altuagoa behar dutela adierazten dute. Aurkikuntza hauek Indefrey (2006)-rekin bat egiten dute. Indefreyren arabera eremu bat ariketa linguistiko batean parte hartzen duenean, hasieran aktibitate neuronal altuagoa erakusteak ariketa honetan jarritako esfortzua isladatzen du. Trebakuntza urteen ondoren aktibitate ahulagoak ariketa modu efektiboago batean prozesatzen dela isladatu dezake, eta orduan H2 sareak H1 sareen anzteakoak dira.

Laburbilduz, tesi honetako emaitzek H2 ikasketaren hasieratik hizkuntza sareak parte hartzen duela adierazten dute, nahiz eta parte hartzea ama-hizkuntzan duenaren ezberdina izan. 3. kapituluak gainera, H2 sareak H1 sareetara hurbiltzen hasteko minutu gutxi batzuetako trebakuntza behar direla erakusten du. Antzeko hipotesiak egin izan dira EEG ikerketetan, non trebakuntzarekin H2 ERP neurgailuak H1 ERP-etara hurbiltzen hasten diren (e.g. Mueller, 2005).

6.4 Azkeneko oharra

Tesi honen helburu nagusia burmuin helduetan hizkuntzarekin lotutako epe-motzeko aldaketak neurtzea zen. Aurreko ikerketek nagusiki luzetarako eta zehar-sekzio diseinuak erabili dituzte, eta ondorioz, finkatuta dauden arauen burmuin erantzunak neurtu dituzte. Bestalde, momentuko eta laborategiko

trebakuntza erabili dituzten ikerketek, eta ondorioz epe-motzeko aldaketak neurtu dituztenak, EEG teknika erabili zuten eta ez dituzte efektuen adierazle anatomikoak azaltzen.

Tesi honen puntu indartsuenetakoa hizkuntza-ikasketaren adierazle anatomikoak teknika ez inbasiboekin neurtu daitezkeela erakusten duela da. Minutu edo ordu gutxien buruan adierazle hauek aldatu egiten direla erakutsi dute emaitzek. Adierazle anatomiko hauek neurtzeko garrantzia Kotz and Elston-Güttler (2004) eta Mueller (2005)-ek aipatu zuten: neurgailu elektrofisiologikoen portaera emaitzak antzematen ez dituzten aldaketak antzeman ditzakete. Ikerketa hauekin bat eginik, 3 kapituluak portaera antzeko mantentzen zen bitartean, burmuin sareak aldatu egiten direla erakutsi zuen. Honetaz gain, MEGean burututako iturri berreraikitzeak sensore mailan antzematen ez diren efektuak kokatzen dituela erakusten du.

Tesi honen beste ezaugarri garrantzitsu bat, aldaketa elektrofisiologikoen batzuk ikusteko trebakuntza minutu gutxi batzuk nahikoa direla da. Nahiz eta sensore mailan, mota honetako aldaketa azkarrak erakutsi izan diren (Davidson and Indefrey, 2009a, 2011; Mueller et al., 2005, 2007, 2008), iturri mailako aldaketak soilik ikastaro bateko partaideak aztertzen zituen luzeratako ikerketetan erakutsi dira (Davidson and Indefrey, 2009b).

Honetaz gain, guk dakigula, hizkuntza-ikasketak oszilazioetan eragiten dituen aldaketak aztertzen den lehen aldia da. H1an esaldi prozesamenduak eragindako oszilazio modulazioak aztertzen dituzten ikerketak dauden arren (Lam et al., 2016), oszilazioetan hizkuntza ikasketak duen eragina ikertu gabe dago. Zoritxarrez, hemen aurkeztutako esperimentuak ez zituen ikasketak eragindako oszilazio aldaketak topatu. 5 kapituluko emaitzetan oinarrituta, analisiak denbora leihotxikietara mugatzean oszilazio aldaketak neurtzea errazagoa dela hipotetizatu zen. Alabaina, 5 kapituluak ez ditu hizkuntza ikasketa efektuak aztertzen.

Hau guztiagatik, bere hutsune guztiekin ere, tesi honek H2 ikasketa aztertzeko ate berri bat irekitzen du. ERFak epe-motzeko hizkuntza ikasketa aztertzeko neurgailu egokiak direla erakusten du. Topatutako efektuen adierazle anatomikoak modu ez inbasiboan neurtu daitezkeela, eta adierazle hauetan aldaketak ikusteko trebakuntza minutu gutxi batzuk nahikoak direla erakusten du. Oszilazioei dagokienez, lan gehiago behar da epe-motzeko hizkuntza ikasketak eragindako plastikotasuna aztertzeko neurgailu egokiak diren edo ez erabakitzeke.

Laburpena

Gizakion burmuina asko ikertzen ari den arren, misterio bat da oraindik. Bide luzea dugu aurretik haren zirkuiteriek hizkuntza bezalako ekintza liluragarrietan nola amaitzen duten ulertzeko. Eta misterioak misterio, umeeek ama hizkuntza arazorik gabe ikasten duten bitartean, bigarren hizkuntza bat ikasi nahi duten helduek ez dituzte horren emaitza arrakastatsuak. Zein prozesu kognitibo gertatzen dira burmuin heldu batean, hizkuntza bat ikasten ari denean?

Gizakiok abilezia eta portaera berriak eskuratzeko eta ingurumen berritara egokitzeko gaitasuna dugu. Ikasketa da, esperientziaren bidez, portaera aldatzeko prozesua. Burmuinaren plastikotasuna, esperientzia eta eskakizunen arabera burmuinak bere antolakuntza anatomiko eta funtzionala moldatzeko duen gaitasuna da (hizkuntza baten ikasketa prozesuan, esate baterako). Era berean, burmuinaren plastikotasunak gaitasun kognitiboen garapena ahalbidetzen du (Uylings, 2006). XX. mende hasieran, garapenaren lehen etapen ostean, aldaketa anatomikoak posible ez zirela uste zuten ikertzaileek (Nieto-Sampedro and Nieto-Díaz, 2005). Alabaina, 50. hamarkada amaieran nerbio-sistemaren anatomia eta funtzionalitatea moldatzeko gaitasunak bizitza osoan zehar mantentzen direla frogatu zen (Liu and Scott, 1958). Plastikotasunaren eztabaida honako proposamenarekin konpondu zen: giza burmuinaren garapena prozesu ugariz dago osatuta eta prozesu bakoitzak plastikotasun profil ezberdina erakusten du (Uylings, 2006).

Denbora eta espazio eskala ezberdinekin egindako analisiak, portaera desberdinekin lotutako plastikotasun profiletara dira sentikorrak. Esate baterako, espazio eskala oso txiki batean, plastikotasun neuronalak konexio sinaptikoen arteko aldaketak aztertzen ditu. Oso zaila da plastikotasun mota hau hizkuntza ikasketarekin erlazionatzea, gizakiongan neurketak egiteko eskuragarri ditugun teknika gehienekin ezinezkoa baita eskala horietan lan egitea. Bestalde, burmuin osoaren eskalako plastikotasuna teknika ez inbasiboen bitartez azter daiteke. Plastikotasun mota hau errazagoa izango da hizkuntza ikasketarekin erlazionatzea, in vivo neurtu baitaiteke.

Hizkuntza baten ikasketak sortutako plastikotasuna neurtzeko, teknika ez inbasiboen arteko egokiena magnetoentzefalografia (MEG) da. MEGak potentzial

post-sinaptikoen gorabeherak neurtzen ditu, 5-10 ms inguruko denbora eskala dutenak (Lopes da Silva, 1991), hizkuntzarekin lotutako prozesuak neurtzeko eskala tenporal egokia eskaintzen du beraz. Linguistikoki eta psikologikoki motibatutako diseinu esperimentalen laguntzaz, teknika honek hizkuntzaren azpiprosesuak 'noiz' gertatzen diren aztertzea ahalbidetzen du: integrazio akustiko-fonologikoa, sintaxia eta semantikaren prozesamendua, integrazio sintaktiko-semantikoa, etab. (Friederici, 2011). Gainera, eremu magnetikoen ezaugarri fisikoak direla eta, MEG teknikak iturrien berreraikitzea ahalbidetzen du (Baillet, 2017). Iturrien berreraikitzearekin lortutako adierazle anatomikoek oso informazio baliotsua eskaintzen dute ikasketan ematen diren aldaketa plastikoak ulertzeko.

Ikerketa gehienak epe luzeko ikasketan zentratu diren arren (Caffarra et al., 2015), egin berri diren ikerketa batzuek epe motzeko ikasketan erakutsi dute interesa (adibidez, Davidson and Indefrey, 2009a). Azken hauek hizkuntza miniaturizatuak erabiltzen dituzte, ikasi beharreko ezaugarriak eta partaideek eskuratutako gaitasun maila hobeto kontrolatzen laguntzen baitute. Diseinu mota honek ikasketa bitartean gertatzen diren garun-aldaketak neurtzea ahalbidetzen du. Epe motzerako ikerketa gehienek gramatika jarri dute arreta (Mueller et al., 2005, 2007, 2008; Davidson and Indefrey, 2009a,b, 2011), hizkuntzei dagokienean ikasteko esparru zailena baita, fonologiarekin batera. Aipatutako ikerketek, ordu (edo minutu) batzuetako ikasketaren ostean, burmuineko seinale elektrikoetan aldaketak somatu zituzten. Alabaina, ikerketa hauek elektroentzefalografia (EEG) bidez neurtu zituzten datuak eta ez dute adierazle anatomikoen berririk ematen.

Tesi hau MEG bidez egindako bi esperimenturen gainekoa da, epe motzeko hizkuntza ikasketari dagozkionak. Hala, jasotako seinale magnetikoak jasandako aldaketen adierazle anatomikoak erakusten ditu. Honez gain, oroimenaren berreskuratze prozesuan oszilazio neuronalek duten funtzioa hobe ulertzeko helburuarekin, partaideen ama hizkuntza erabilia egindako hirugarren esperimentu bat ere barnebiltzen du.

6.5 Lehen esperimentua: Gramatika ikasketa

Lehen esperimentuak gramatika arau berri baten ikasketa ikertzen du. Ikasketaren (praktikaren) aurretik, bitartean eta ondoren MEGarekin bildutako garun jarduera ebokatuaren iturri berreraikitzeak aurkezten ditu. Esperimentuko bi saioak bi egun jarraietan egin ziren eta gramatika ikasketa, kontrol-urratzeak era kontzientean antzemateko ariketa bat eginda ikertu zen. Asmatze proportzioak eta MEG seinaleak ikasketaren aurretik, bitartean eta ondoren grabatu ziren eta ama hizkuntzan (H1)

jasotako grabaketekin alderatu. Partaideei Euskarazko (H2) izen sintagmen zenbaki konkordantzia irakatsi zitzaizkien, hau da, arau morfosintaktiko bat. Euskara-Gaztelera kognatuak erabili ziren hiztegirako, zama semantikoa gutxitu eta era horretan urraketa sintaktikoen prozesamendurako baliabideak libre uzteko (Mueller et al., 2008). Praktika blokeen ostean, orokortze ariketa bat egin zen, non partaideek arau morfosintaktiko beraren gaineko erabakitze ariketa bat egin behar zuten, hiztegi berria erabilita (hau ere kognatua). Hiztegi kognatuarekin arau gramatikalak azkar barneratuko zirela izan zen ikerketa honen hipotesia. Praktikaren aurretik partaideek ezin izan zuten izen sintagmen gramatikaltasuna modu egokian epaitu. Praktikako lehen blokean eta arau gramatikalaren azalpenaren ostean, ordea, partaideen erabakia zuzena zen portzentaje oso altu batean. Praktikako beste blokeetan eta orokortze blokean erantzun zuzenen proportzioa mantendu zuten. Helduek gramatika ikasketa azkarra izan dezaketela iradokitzen du honek, ikasketa intentsibo baten bitartez egiten denean behinik behin.

Gramatika urraketen prozesamenduan parte hartutako sareak, praktikarekin aldatu ziren ordea. Praktikako lehen blokean, eskuin lobulu tenporalean eta eskuin aurre lobuluan lokalizatu zen gramatikaltasun efektua. Burmuin eremu hauek akats antzematearekin erlazionatu izan dira lehenago ere (Indefrey et al., 2001). Gainera, HERA (hemispheric encoding/retrieval asymmetry) modeloaren arabera, eskuineko aurre garun-azala oroimen berreskurapenarekin dago erlazionatuta (Habib et al., 2003). Alabaina, hurrengo praktika blokean, gramatikaltasun efektua ezker lobulu parieto-tenporaletan lokalizatu zen. Azkenik, hirugarren praktika blokean eta orokortze ariketan, efektua ezker lobulu tenporalean lokalizatu zen. Aldaketa hauek 'arau gramatikalizazio' prozesu bat bezala interpretatu daitezke, non partaideek denbora behar duten arau honen jakintza denbora errealeko prozesamenduan txertatu ahal izateko (McLaughlin et al., 2010).

6.6 Bigarren esperimendua: Esaldien ulermena

Bigarren esperimendua esaldiak entzuteko ariketa bat erabiltzen du hizkuntza ikasketa aztertzeko. Kasu honetan, partaideek (jatorri ingelesekoak) bai ama hizkuntzan (H1), eta baita hizkuntza ezezagun batean (H2, Gaztelera) ere entzun zituzten esaldiak, MEG seinaleak grabatzen ziren bitartean. Ondoren, MEGetik kanpo, esaldi horiek hizkuntza berrian ulertzeko moduko hiztegia irakatsi zitzaizkien. Hiztegia ikasteaz gain, hiztegi berriarekin osatutako esaldi osoen entzumena praktikatu zuten. Hurrengo egunean, partaideek ama hizkuntzan eta ikasi berri zuten hizkuntzan entzun zituzten esaldiak, MEG seinaleak grabatzen ziren bitartean eta MEG saio bakoitzaren ondoren ulermen frogak egin ziren. Lehenengo eguneko

frogan, partaideek hitz solte batzuk errekonozitu zituzten baina ez ziren gai izan esaldi osoak ulertzeko. Bigarren egunean ordea, ulermen frogako erantzunak zuzenak izan ziren. Honek ez du soilik helduengan hiztegiaren ikasketa azkarra izan daitekeela iradokitzen, ikasitako hiztegia mintzamenetik segmentatu eta identifikatu daitekeela baizik, eta baita hitz ezberdinen esanahiak esaldiarena lortzeko batu daitezkeela ere, praktika saio bakarraren ondoren.

Esperimentu honetan, esaldiak entzutearen eraginez sortutako jarduera oszilatarioa aztertu zen. Horretarako isiltasunaren eta esaldien arteko potentzia aldaketak neurtu ziren, frekuentzia banda bakoitzarekin. Potentzia aldaketak hizkuntza sarean lokalizatu ziren bai ama hizkuntza eta baita hizkuntza berria entzutean ere, nahiz eta potentzia aldaketak handiagoak ziren azken kasu honetan. Emaidza hauek, hizkuntza berriek hizkuntza saretan informazio prozesamendu handiagoa eta beste burmuin eremuetan inhibizio altuagoa behar dutela iradokitzen dute. Ez zen ebidentzia sendorik topatu hizkuntza berriaren ikasketak eragindako potentzia aldaketetan. Emaidza hauek, esaldi oso bati erantzunez sortutako oszilazioek esaldi horren entzumenean gertatzen diren prozesu asko jasotzen dituztela eta horietako prozesu batzuetan gertatu daitezkeen aldaketa txikiak difuminatu egiten direla iradokitzen dute.

6.7 Hirugarren esperimentua: Oroimenaren berreskuratzea H1an

Hirugarren esperimentuan, H1an oroimenaren berreskurapena ikertu zen, entzutezko materialak erabiliz. Partaideek 50 hitzeko zerrendak buruz ikasi zituzten. Zerrenda bakoitzeko hitz guztiak banaka agertzen ziren pantailan eta guztiak ikusi ostean, partaideek 5 minutuko praktika burutzen zuten zerrenda buruz errepasatuz. Azkenik, antzemate ariketa bat egin zen entzutezko materialekin. Praktika eta antzemate ariketa bi egoera ezberdinetan burutu ziren, begiak itxita eta begiak irekita. Partaideek begiak itxita zituztela hitz gehiago antzemango zituztela hipotetizatu zen. Alabaina, begiak ixteak partaideen erantzunak ez dituela aldatzen erakusten dute emaitzek.

MEG uhinei dagokienean, begiak ixteak sentzore parieto-okzipitaletako alfa frekuentzia bandan (8-13 Hz) potentzia igoera eragin zuen. Bestalde, gogoratutako eta ahaztutako hitzen eraginez gertatutako alfa modulazioak sentzore tenporaletan topatu ziren. Azken emaitza honek oszilazioak tau izeneko erritmo baten eragina direla ondorioztatzea ahalbidetzen du. Honez gain, alfa eta tau erritmoen arteko interakziorik ez zen topatu. Emaidza hauek entzutezko oroimen ariketetan tau

eritmoaren modulazioak oroimenaren errendimenduarekin erlazionatuta daudela iradokitzen dute, eta hauek MEGarekin neurtu daitezkeela, EEGarekin ez bezala. Eraitza hauek tau eta alfa oszilazioen rola ezberdina dela iradokitzen dute, nahiz eta frekuentzia banda antzerakoan oszilatzen duten. Hala, oszilazio analisien emaitzak interpretatzeko garaian, frekuentziaz gain efektuen topografia edo/eta lokalizazioa ere hartu behar dira kontutan.

6.8 Eztabaida orokorra

Lehen esperimentuko emaitzak bat datoz epe motzeko ikasketaren gaineko beste emaitzekin (Mueller et al., 2008, 2007, 2005; Davidson, 2010; Davidson and Indefrey, 2009a), praktika ordu (eta baita minutu ere) gutxi batzuk nahikoak direla burmuineko sare funtzionalak aldatzeko erakutsiz, sare funtzional hauek H1 prozesatzean agertzen diren sareen antza hartzen dutelarik. Bestalde, emaitza hauek epe luzeko ikasketa emaitzekin bateraezinak direlako irudipena eman dezakete. Luzetarako ikerketek hizkuntza ikastaro ofizialetako lehen urteko ikasleek H2n erakusten dituzten gramatikalitate efektu patroiak eta H1n erakusten dituztenak ezberdinak direla erakutsi dute (McLaughlin et al., 2010). Epe motzeko ikasketa ikerketetan partaideek hizkuntzen frakzio txikiak praktikatzan dituztela eta frakzio beretan aztertuak direla izan daiteke azalpen posible bat. Alabaina, luzetarako ikerketetako partaideek hizkuntza baten ezaugarri anitzak ikasten dituzte, baina frakzio txiki batean dira aztertuak. Gerta daiteke aztertuak diren frakzio horiek oraindik gramatikalizatu gabe egotea (McLaughlin et al., 2010). Beste azalpen posible bat, ikasketa intentsiboan gertatzen diren burmuin aldaketak, praktika mantendu ezean, epe luzera galtzen direla izan daiteke.

Bigarren esperimentuan ikasketak aktibitate oszilatarioetan sortutako modulazio argirik ez zen topatu. Azalpen bat izan daiteke, esaldiak entzuteak funtzio kognitibo ezberdinetan baitan dagoenez (segmentazioa, hitzen antzematea, esanahien integrazioa, etab.) praktika saio bakarra nahikoa ez izatea aktibitate oszilatarioan aldaketak eragiteko. Beste aukera bat izan daiteke, aldaketak gertatu izana baina hauek ezin antzeman izatea. Burututako analisiak funtzio kognitibo ezberdinekin lotutako aktibitate oszilatarioa erakusten du. Analisia oszilazio tarte txikiagotan zentratuko balitz, agian aktibitate oszilatarioko aldaketak ikusgai egon lirateke, hirugarren esperimentuan gertatzen den antzera.

Bigarren hizkuntzen ikasketen ikerketan ohiko galdera da ea hizkuntza sarea ikasketa prozesuaren hasieratik murgilduta dagoen edota bestelako funtzio kognitibotaz arduratzen diren burmuin areak biltzen diren H2a prozesatzeko

(Indefrey, 2006). Lehenengo esperimentuak H1 eta H2ren erantzunen arteko konparaketa estatistikoa aurkezten ez duen arren, konparaketa kualitatibo bat eskaintzen da. Bigarren praktika bloketik gramatikalidade efektua ezker lobulu tenporalean eta ezker behe aurre giroan kokatzen da, biak modelo ezberdinek azaldutako hizkuntza sareko eremuak direlarik (Hagoort, 2016; Friederici, 2011). Hala ere, analisi estatistikoek efektua blokez bloke aldatzen diren patroik honen azpieremetutan kokatzen du. Sare hauen gainjarri partzialak bat egiten dute luzetarako MEG ikerketa batekin, non estatistikoki efektua erakusten zuten burmuin eremuak obulu tenporalaren barruan aldatu egiten ziran saio batetik bestera (Davidson and Indefrey, 2009b).

Bestalde, bigarren esperimentuan burmuin mailako H1 eta H2 arteko aktibitate oszilatarioan konparaketa estatistikoa aurkezten da. Emaitzek iradokitzen dute H2n erantzun oszilatarioak anplitude handiagokoak direla H1ekoekin alderatuz gero. H2n alfa frekuentziaren desinkronizazio handiagoa topatu zen lobulo tenporaletan. Alfa desinkronizazio handiagoak informazio prozesamendu gaitasunarekin erlazionatu izan da (Klimesch et al., 2007; Hanslmayr et al., 2012). Bigarren esperimentuko patroik hauek adierazten dute lobulu tenporalek informazio prozesamendu handiagoa behar dutela H2 entzuten, eta ariketan parte hartzen ez duten eremuek inhibizio altuagoa dutela. Emaitza hauek Indefrey (2006)-ren emaitzekin bat datoz, ikasketa prozesu hasieran pertsonak ariketa bat burutzeko esfortzu handiagoa behar dutela eta hau H1an baino intentsoago den burmuineko eremuen erreklutamendu batean islatzen dela diote emaitza hauek. Hizkuntza baten maila batera iristean, ariketak errazago gauzatzen dira eta, ondorioz, burmuineko aktibitatearen patroiak H1ko patroietara hurbiltzen dira.

Laburbilduz, tesi honek helduen hizkuntza ikasketa ikertzeko ate berri bat irekitzen du. Tesi honen emaitzek burmuineko hizkuntza sare H2 ikasketa prozesuaren hasieratik presente dagoela adierazten dute, nahiz eta sarearen erantzuna H1koaren ezberdina den. Bestalde, lehenengo esperimentuak praktika minutu batzuk (ikasketarekin bat datozen) burmuin sareetan aldaketak sortzeko nahikoak direla erakusten du. Sorrarazitako eremu magnetikoak epe motzeko ikasketa ikertzeko tresna egokia dela erakutsi da, eta hauen korrelatu anatomikoak modu ez inbasiboan neurtzea posible dela. Bigarren esperimentuak, hizkuntzaren beste aspektu batzuetan aldaketak antzemateko, praktika saio gehiago behar direla erakusten du, denbora epe laburrago batean oinarritutako analisi batek aldaketak antzeman ditzakeela baztertu gabe.

English version

Introduction

The human brain is an organ that despite being widely studied remains a mystery. A great deal of work is still needed to understand how its circuitry results in amazing actions such as, for example, language. And the mystery inside the mystery, while most children master their native language (L1) without major difficulties, adult learners of a second language (L2) often show poorer levels of achievement. Which processes take place in the adult brain while learning a language?

Current neuroimaging techniques allow us to record brain activity during L2 processing. The arrival of these advances has recently increased the interest in neuroimaging studies in order to measure changes in brain activity related to L2 learning. Table 1 summarizes the current literature on L2 learning for studies that use common neuroimaging methods as a function of the type of learning that was studied, from on line training to group comparisons with years of experience with L2. The different colors represent the different tasks (production, comprehension, grammatical judgement). This table clearly shows that although there is a substantial amount of work in different domains of Second Language Acquisition (SLA), using a variety of techniques, most of the studies focus on the outcome of learning and not on the learning process itself.

This thesis investigates how brain changes occur during L2 learning by using magnetoencephalography (MEG) recordings, focusing on short-term changes. In order to study those changes, this thesis presents a series of experiments in which participants were trained in the lab and magnetic signals were recorded prior to and after this training (lab-training). Moreover, for one of the experiments magnetic signals were also recorded *during* the training process (on-line training). Compared with longitudinal and cross-sectional studies, lab (and on line-training) paradigms give us the opportunity to measure brain changes that occurred just after learning happened, therefore, measuring recent changes in brain activity. Moreover, on-line training paradigms also allow us to look at what is happening while these memories are being created, while people learn a new language. To date, only phonological lab training studies (Zhang et al., 2000, 2001) have provided evidence of the anatomical

	Online Training	Lab Training	Formal Course	Cross-sectional	
fMRI			Indefrey et al. 2005 Wang et al. (2003) Sakai et al. 2004	Suh et al. 2007 Yokoyama et al. 2006 Rüschemeyer et al. 2006 Rodríguez-Fornells et al. 2005 Pillai et al. 2004 Xue et al. 2004 Vingerhoets et al 2003 Perani et al. 2003 Ding et al. 2003 Mathendra et al. 2003	Luke et al. 2002 Hasegawa et al.2002 Pu et al. 2001 Chee et al. 2001 Hernandez et al. (2000,2001) Chee et al. 1999 Dehaene et al. 197 Illest et al. 1999 Perani et al. (1996,988) Klein et al. 1995
EEG	Davidson and Indefrey (2008,2011)	Batterink and Neville 2013 Morgan-Short et al. 2012 Mueller et al. (2005,2007,2008) Morgan-Short et al. 2010	Bañón et al. 2014 McLaughlin et al. 2010 Osterhout et al. 2006	Proverbio et al. 2012 Foucart and Frenck-Mestre 2011 Zawiszewski et al. 2011 Dowens et al (2011,2010) Moreno et al 2010 Guo et al 2009 Frenck-Mestre et al. 2008 Kotz et al. 2008 Chen et al 2007 Isel 2007	Rossi et al. 2005 Hahne and Friederici 2001 Hahne 2001 Weber-Fox and Neville 1996
MEG	EXPERIMENT 1	Hultén et al. 2014 Zhang et al. (2000,2001) EXPERIMENT 2	Davidson & Indefrey 2009		

■ Syntactic processing
■ Comprehension
■ Speech production
■ Phonology

Table 1: A classification of several different studies on L2 speakers and learners. Columns show the type of study (on line training, lab training, formal course (longitudinal) or cross-sectional study). Rows represent the technique for neuroimaging. (Magnetoencephalography (MEG), Electroencephalography (EEG), functional Magnetic Resonance Imaging (fMRI)).

correlates of these short-term changes. For other language domains anatomical correlates of short-term changes remain understudied (see Table 1).

To the best of my knowledge, this thesis presents the first studies providing anatomical correlates of short-term changes related to grammar and vocabulary learning, and the first study where training was carried out during MEG recordings (see Table 1). Furthermore, they are also the first ones that compare responses to both the native as well as the newly learned language in lab- and on line-training paradigms.

In order to isolate short-term learning-related brain changes from the brain responses of already consolidated rules, one approach is to study learning at initial stages. The benefit of this approach is that, if participants who are trained in the experimental sessions have no knowledge of the L2, the brain responses that are recorded cannot originate from consolidated memory. Moreover, there is no problem of initial proficiency (baseline) matching across participants.

Furthermore, it is important to bear in mind that language and speech are processes that occur over a relatively short interval of time. Sentences begin and

end over the course of a few seconds, and the relations among individual words and grammar are embedded within those sentences. To understand the brain's response to these processes one would need an imaging technique that is able to isolate responses to individual words and at the same time give us information about the anatomical correlates of that activity. MEG is uniquely suited to these requirements. Firstly, due to its temporal resolution it can capture low-frequency fluctuations of post-synaptic potentials of around 5-10 ms and therefore responses to single words. Second, due to its spatial resolution, anatomical correlates of the measured activity can be obtained with the proper mathematical methods. Moreover, it allows subjects to listen and speak during the recordings for long time periods, which allows the use of several different language tasks.

The first part of this thesis introduces theoretical, empirical and methodological background. **Chapter 1** introduces the different approaches that have been used to study language learning. The type of brain activity recorded in this thesis and the MEG technique that records them are explained in **Chapter 2**.

The second part presents the different experiments. The first studies explore L2 learning at initial stages: **Chapter 3** presents a grammar learning experiment and **Chapter 4** is an experiment on vocabulary learning and short sentence comprehension. Afterwards, **Chapter 5** presents a third experiment on memory retrieval enhancement that can help to better understand the neural mechanism of memory retrieval and its potential enhancement (which is also important for language learning). This chapter is intended to facilitate the interpretation of the results from Chapter 4.

Finally, **Chapter 6** summarizes all the previous results and provides a general discussion of them, related to the existing theoretical background of L2 processing and learning.

Part I

Theoretical and empirical background

Chapter 1

Language learning as an adult

The aim of neurolinguistics is to understand how the organization and physiology of the brain gives rise to language function. In this thesis, the aim is to understand how the structure and function of the language networks contribute to the short-term acquisition of newly-learned languages, as well as memory for words. This chapter introduces the concept of brain plasticity, as well as the techniques and methods to study it.

1.1 Learning, memory and brain plasticity

Humans have the ability to acquire new sets of skills, forms of behaviour, and adapt to new environments. Learning refers to the process of change of behaviour due to experience. Memory, in contrast, refers to the product of change: the permanent records that underlie this adaptation (Anderson, 1995). Both memory and learning take place in the nervous system. However, for a long period research on memory and learning focused on measuring the behavioural changes in order to deduce the mechanisms behind learning (Schumann et al., 2004). On the other hand, modern neuroscience studies how brain functional and structural changes are related to behavioural findings (Diamond and Amso, 2008).

Brain plasticity is the ability of the brain to reshape its organization and function depending on demands or experience (e.g. during language acquisition) and, in turn, brain plasticity allows the development of cognitive capabilities (Uylings, 2006). During the early 20th century researchers believed that anatomical changes were not possible following development (Nieto-Sampedro and Nieto-Díaz, 2005). Nevertheless, in the late 1950s Liu and Scott (1958) showed that the capacity of functional and anatomical modification of the nervous system exists throughout the lifespan, although it has been suggested that plasticity decreases thorough the lifespan

(Pascual-Leone et al., 2012). The controversy of brain plasticity during adulthood was solved by proposing that the development of the human cortex is composed by different neural processes, and that each process has a certain plasticity profile (Uylings, 2006). Two main categories have been proposed to classify these neural processes and plasticity profiles: major anatomical changes (e.g. long distance axonal rewiring) which are believed to not occur after completion of development, and local scale changes (e.g. local dendritic and synaptic alterations) which do not stop in adulthood. Nonetheless, this does not imply that the capacity for plasticity remains unchanged during life (Pascual-Leone et al., 2012; Uylings, 2006).

Different spatial and temporal scales of analysis would be sensitive to the different plasticity profiles that can be linked to different behavioural outcomes. For instance, at a small spatial scale changes of synaptic connexion between single neurons can be assessed. For instance, animal research has focused on changes in dendritic fields due to experience under the assumption that dendritic space is highly correlated with synaptic numbers (Kolb et al., 1998). This research line usually compares two groups of animals: one group is placed in laboratory cages and the other is housed in a more stimulating environment. After death the dendritic space of groups is compared. Greenough and colleagues found that dendritic fields of 'enriched experienced animals' increased about 20% compared to cage animals (Greenough and Volkmar, 1973; Volkmar and Greenough, 1972). Moreover, they found that more blood capillaries and astrocytic material is found together with increase synapses per neuron in enriched experienced groups (e.g. Sirevaag and Greenough, 1987).

Similar procedures have been used to link dendritic changes and human behaviour. Jacobs et al. (1993) found that the extent of dendritic arborization in Wernicke's area, an important region within the language network, is related to the amount of education: the higher the education level, the more extensive the dendritic arbor. Furthermore, they looked at the relationship between behaviour and brain structure, considering that functional abilities of people would correlate with neuronal structure. Based on the observation that females have superior verbal abilities compared to men (see Kolb et al., 1996, for a review), they compared males and females and found that females have more extensive dendritic arbors in Wernicke's area.

Nonetheless, this form of plasticity is hard to link to language learning. First of all, although it is intriguing to assume that these dendritic changes are reflecting changes in learning, there is little evidence for this (Kolb et al., 1998). Moreover, these changes occur at a scale that is inaccessible to most current measurement approaches in humans. Even if it was accessible, it is not always possible to know where in the brain to look for learning dependent changes. And even, if such changes were found

in human dendritic space, language learning comprises many subprocesses so that it would be hard to link the dendritic changes to specific language learning changes.

Plasticity at the scale of the entire brain can be measured, for instance, as changes in grey matter thickness (Martensson et al., 2012; Klein et al., 2014) or changes in the functional connectivity among areas (Ghazi Saidi et al., 2013; Price, 2010). This form of plasticity is more accessible due to non-invasive neuroimaging methods which enable the in-vivo examination of the human brain and, therefore, facilitate the association of plasticity and language learning. The following sections explain how plasticity at the entire brain scale can be measured and what is known about plasticity in the language network.

1.2 Techniques to study plasticity at the entire brain scale

Neuroimaging techniques are appropriate tools to study structural and functional changes subtending neuronal plasticity in humans (Rossini et al., 2003). **Magnetic Resonance Imaging** (MRI) is an imaging technique that has relatively high spatial resolution for anatomical detail. It is used to measure structural brain indexes such as grey matter thickness or fiber-tracks (connections) among regions. Functional MRI can also be used to measure brain activity (indirectly) although its temporal resolution is low (around 2 seconds). It measures changes in the oxygenation of the cerebral blood as a result of neuronal hemodynamic changes that occur in a scale of several seconds (Ogawa et al., 1990). It is thought that fMRI is well suited to capture the areas that are involved in a language task (Matthews et al., 2003). Nevertheless, it is a poor match to the time scale of sentence processing because changes of the measured signal occur on the scale of multiple seconds, but words or sentences evolve more quickly than that. Therefore using a technique with higher temporal resolution would be more suitable to examine language-related brain plasticity.

Unlike fMRI, **Electroencephalography** (EEG) and **Magnetoencephalography** (MEG) are techniques with higher temporal resolution (Schomer and da Silva, 2010; Hämäläinen et al., 1993, respectively). They measure fluctuations of post-synaptic potentials, which have an approximate temporal scale of 5-10 ms (Lopes da Silva, 1991), and are thus better suited for the time scales of language related processes. Along with psychologically- and linguistically-motivated experimental designs, these techniques enable us to study some physiological correlates of 'when' the different sub-processes occur: acoustic-phonological integration, syntactic and semantic processing, or syntactic-semantic integration (e.g. Friederici, 2011).

An important difference between EEG and MEG is that EEG measures the

electrical field of the currents generated in any direction while MEG can only measure magnetic fields generated by currents tangential to the cortex (Hansen et al., 2010). On the other hand, due to the physical properties of electrical fields, EEG is strongly degraded when travelling across head tissues, but this effect is limited in MEG due to the physical properties of magnetic fields, resulting in an improved spatial resolution (Baillet, 2017). Consequently, studies using MEG offer higher anatomical localization of the measured effects. EEG studies do not often report which brain areas are responsible for which features of the waveforms. The experiments of this thesis take advantage of the spatial and temporal precision of the MEG to investigate short-term language learning related plasticity.

In addition, three elements are needed to investigate plasticity related to acquiring a new capability: a description of the brain system that supports a function, the neural characterization of the adjustment of that system in order to integrate the new capability and, finally, a link between the brain and behavioural changes that could explain the functioning of that system when the new capability is in use. The spatio-temporal resolution of MEG allows us to obtain anatomical correlates of brain activity that occurs in short time intervals (Hämäläinen et al., 1993), resulting in an appropriate tool that provides an entire brain scale description of the network supporting different language subsystems. It measures entire brain scale functional changes and permits the in-vivo examination of human brain and, therefore, facilitates the association with behavioural changes. In sum, MEG is an appropriate technique to study entire-brain scale plasticity related to language learning (Rossini et al., 2003).

1.3 Language network plasticity

This section describes possible cortical areas that support language processing and language related plasticity profile of the mentioned areas.

Friederici (2011) proposed a model that suggests the spatial and temporal brain localization of the different language subsystems in speech comprehension. The model consists of several sub-processes that take place in a serial cascade with partly parallel processes (see Figure 1.1). Friederici's model is based on evidence from ex-vivo and fMRI studies to suggest the anatomical correlates of the different language subsystems; evidence from electrophysiological studies has been used to suggest the temporal windows where the processing of the subsystems occur. Based on this model, the first acoustic-phonological analysis of the input occurs in auditory cortex and adjacent areas (Binder et al., 2000; Hall, 2002) within (approximately) the first 150 ms after speech onset (Näätänen and Alho, 1997; Poeppel et al.,

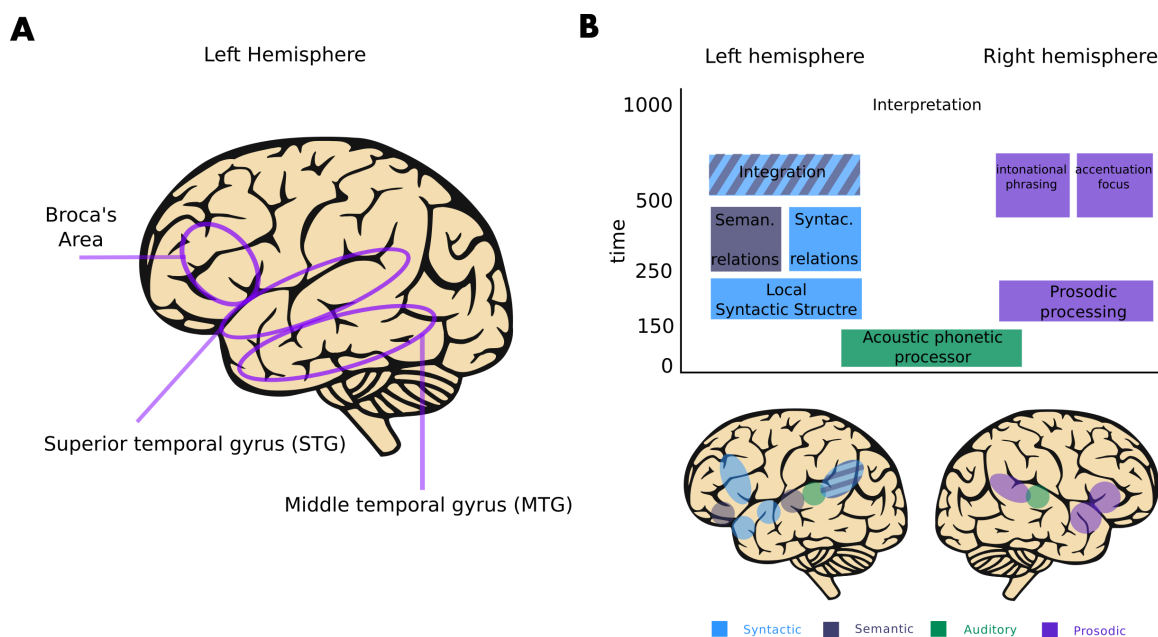


Figure 1.1: Model of auditory sentence comprehension. Panel A labels the areas from the language network. Panel B shows an schema of 'when' and 'where' the different sub-processes take place. (Adapted from Friederici, 2011)

1997; Phillips, 2001). The next phase is initial syntactic processing, where word category information is recovered, thought to occur between 150 and 250 ms after onset (Friederici and Weissenborn, 2007) in the left inferior frontal gyrus (IFG) (Rüschemeyer et al., 2005; Brauer and Friederici, 2007). In the next phase, syntactic and semantic relations are processed, for example, computation of the relations between the verb and its arguments (e.g., who is doing what to whom). This processing occurs between 250 and 500 ms (see Penke et al. (1997); Angrilli et al. (2002) for syntactic and see Lau et al. (2008) for semantic). Syntactic relations are processed in left anterior temporal lobe and IFG (Humphries et al., 2006; Friederici et al., 2000, 2003, 2010), while semantic relations are processed in left posterior temporal lobe and IFG (Friederici et al., 2003; Obleser and Kotz, 2010). Afterwards, there is a processing phase during which syntactic and semantic information interact with each other and are integrated to achieve interpretation. This phase occurs between 500 and 1000 ms (Gunter et al., 2000; Kuperberg et al., 2003, 2006) and has been localized at left posterior superior temporal gyrus (STG) (Grodzinsky and Friederici, 2006). In parallel to all these processes, phonological and prosodic processes are thought to take place mainly in the right hemisphere. Regarding phonology, identification of phonemes and word forms occurs between 150 and 250 ms (Friederici, 2002). Regarding prosody, intonational phrasing and accentuation focus would occur around 500 ms (Steinhauer et al., 1999).

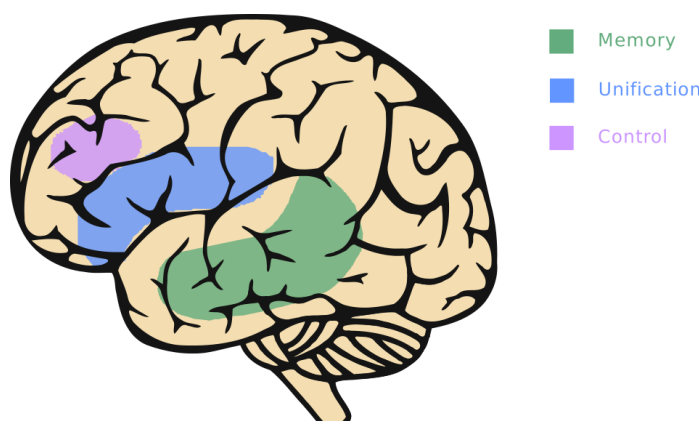


Figure 1.2: MUC model for language processing (Hagoort, 2016).

Hagoort (2016) proposed another model for language processing with three main components: The Memory, Unification and Consolidation model (MUC) (see Figure 1.2). Regions in temporal cortex support the memory component (Hagoort, 2003, 2005, 2009), which refers to linguistic knowledge representations that have been consolidated in memory (Davis and Gaskell, 2009). Depending on the knowledge type, different regions of the temporal cortex are involved. Unification relies on frontal regions (Hagoort and Indefrey, 2014). The unification component mainly takes place in frontal regions, where the elements extracted from memory are combined in novel ways (Hagoort, 2005). Different unification processes, such as semantic, phonological and syntactic, recruit different brain structures apart from the frontal regions. Finally, the Control component selects the appropriate target language to fulfill social interaction requirements. The dorsolateral prefrontal cortex is believed to be the main hub of the control component (Kristensen et al., 2013).

These two models are examples that show how different models divide language processing in different subsystems. A commonality is that both models propose that language processing is divided in different subsystems and each of those subsystems relies on different cortical areas, confirming Sander's suggestion (Sanders et al., 2008). It is known that during certain periods of development the plasticity potential is higher compared to other developmental periods (Knudsen, 2004). According to Zilles (1978) different cortical areas have different plasticity profiles and, thus, the capability of learning may differ across language subsystems (Uylings, 2006). For instance, it has been suggested that while delays in L2 acquisition seem to have a minimal effect on semantics, deficits occur in syntactic and phonological processing (Sanders et al., 2008).

Moreover, although there are some anatomical and functional differences among models, there are also common areas across models; including the left temporal lobe

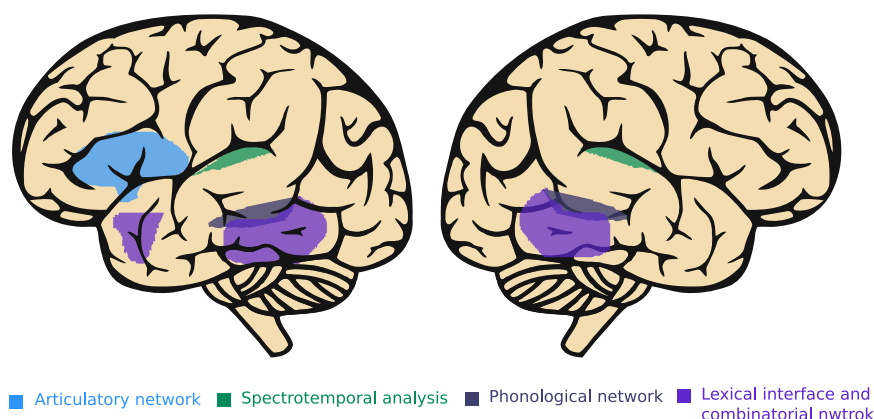


Figure 1.3: Hickok and Poeppel model for language processing (Hickok and Poeppel, 2007).

and left inferior frontal gyrus. These areas have also been included in other type of language processing models such as the one proposed by Hickok and Poeppel (e.g. 2007).

This model suggests that there are multiple routes to lexical access which are implemented in parallel channels. It proposes that ventral stream is involved in processing speech signals for comprehension (speech recognition) whereas a dorsal stream is involved in translating acoustic speech signals into articulatory representations (see Figure 1.3). The bilateral dorsal surface of the superior temporal gyrus (STG) is proposed to be involved in the spectrotemporal analysis of the acoustic input. Phonological-level processes are suggested to occur in the posterior half of the superior temporal sulcus (STS). Posterior middle and inferior portions of the temporal lobe are suggested to correspond to link phonological and semantic information, whereas more anterior locations are in charge of combinatorial processes. This model locates the articulatory network in the left inferior frontal gyrus (IFG) and dorsal premotor areas.

Functional changes due to language learning have been found in both IFG and the temporal lobe (Indefrey, 2006). For instance, Chinese native speakers were tested three, six and nine months after starting to learn Dutch (Indefrey et al., 2005). Participants listened to Dutch sentences and had to decide if the sentence matched a picture on a screen while they were scanned in the MRI. The BOLD response in the IFG to sentence listening changed across the three sessions. Moreover, it has also been shown that the response of the IFG changed after two months training on verb inflection (Sakai et al., 2004). Participants were given a verb stem and had to produce the past form of the verb. The measured BOLD signal at the IFG was found to statistically increase after training. Moreover, the BOLD response after the training correlated with the behavioural performance of the task. In a follow up study, they

studied the same task but on a group of learners who had studied English for six years (Tatsuno and Sakai, 2005). In this case, they found that the BOLD response at the IFG was weaker for better performers than for bad performers. Indefrey (2006) suggested that this pattern inversion could reflect the task effort: early beginners need more effort to perform the task and after years of practice the same task becomes less difficult.

Regarding functional changes in the temporal lobe, it has been reported that the BOLD response in the bilateral temporal pole and left posterior temporal gyri is weaker when listening to L2 compared to L1 in learners with moderate L2 proficiency (Perani et al., 1996). This is not the case for highly proficient learners, whose BOLD response in these regions does not differ when listening to L1 versus L2 (Indefrey, 2006). In a longitudinal study (Davidson and Indefrey, 2009b) studied how word order violation was processed by German natives learning Dutch in a formal course. Participants were tested in the MEG for three different sessions, at the beginning of the course, after two weeks and after three months. Participants had to read a sentence and had to decide if the picture coming after was matching. No difference was found between violation and control sentences in the first session. In the second session, the brain activity in the left superior temporal areas differed for the two conditions. However, in the third session the difference was localized in left frontal areas.

Thus, plasticity in the IFG and temporal lobe due to language learning has been found in long-term and medium-term learning. However, it still remain understudied how brain functionality changes during short-term language learning, in the IFG and temporal lobes, and in the rest of the brain. This thesis presents two experiments (Chapter 3 and Chapter 4) that aim to contribute data to this gap.

Moreover, plasticity can be also studied at different temporal scales. Plastic changes in the organization of a function can be transient or long lasting (Knudsen, 2004). It has been shown that short-term and long-term learning of motor tasks induce different type of plastic changes (Rossini and Melgari, 2011). Electrophysiological studies focused on long-term and short-term adult language learning are reviewed in the following sections respectively.

1.4 Long term language learning in adulthood

In past research, neuroimaging techniques have been used in combination with different paradigms to study brain plasticity in different language subsystems. On the one hand, cross-sectional studies compare groups of L2 speakers with different

characteristics: for example learners with early exposure vs. late exposure, learners with different learning strategies, etc (e.g. Kotz et al., 2008; Hahne, 2001). On the other hand, longitudinal studies follow the same group of participants that undergo a formal course. The same participants are tested usually before, in the middle and after some period of formal training (e.g. Davidson and Indefrey, 2009b; McLaughlin et al., 2010).

Recent reviews have stressed that different language subsystems (e.g., semantics, syntactic, phonology) may rely on different cortical networks (Sanders et al., 2008). Regarding grammar learning, while there is now a collection of areas implicated by bilingual fMRI studies (e.g. Indefrey, 2006; Sebastian et al., 2011), to date there have been few comparisons of localized activity measured with electrophysiology. FMRI studies reviewed by Indefrey (2006) that focus on morpheme inflections have shown reliable differences during L1 and L2 processing, showing stronger involvement in left posterior areas in early stages of learning. In the experiment described in Chapter 3, MEG is used to obtain source reconstruction of electrophysiological effects to uncover some of the broad areas that are involved in recognizing grammatical violations in learners.

Learning to use grammatical relations or rules often involves learning to recognize dependencies that occur over time as words of a sentence are understood or produced. Morphosyntactic agreement relations such as gender, person or number agreement are, for many European languages (such as Spanish and German), characteristic examples of grammatical processes where morphosyntactic elements of one part of a phrase or sentence systematically covary with other elements (Bybee, 1985). In studies of grammatical learning, the response to a so-called 'critical word' or morpheme within a sentence (i.e., the point in the phrase where the relation can be first recognized) can be measured before and after learning to better understand how changes in behavioral recognition are related to changes in the brain responses (Osterhout et al., 2006). A recent review by Caffarra et al. (2015) summarized the main event related potential (ERP) components found in recent longitudinal or learning studies.

To date, the electrical P600 in response to morphosyntactic violations has been seen in a variety of short-term learning settings, L1-L2 pairings, and experimental designs (Weber-Fox and Neville, 1996; Hahne, 2001; Rossi et al., 2006; Frenck-Mestre et al., 2008; Kotz et al., 2008; Sabourin and Stowe, 2008; Weber and Lavric, 2008; Dowens et al., 2010; Moreno et al., 2010; Dowens et al., 2011; Foucart and Frenck-Mestre, 2012a; Pakulak and Neville, 2011; Schmidt-Kassow et al., 2011a,b; Zawiszewski et al., 2011; Foucart and Frenck-Mestre, 2012b; Xue et al.,

2013; Bañón et al., 2014; Lemhöfer et al., 2014; Tanner et al., 2013). Nevertheless, it is not the only component that reflects grammar learning.

The N400 component has also been used to characterize L2 learners (Weber-Fox and Neville, 1996; Proverbio et al., 2002; Kotz et al., 2008; Weber and Lavric, 2008; Guo et al., 2009; Tanner et al., 2009; McLaughlin et al., 2010; Zawiszewski et al., 2011; Foucart and Frenck-Mestre, 2012b; Xue et al., 2013; Tanner et al., 2013). While native speakers show an N400 component in response to a semantic violation and a P600 component in response to a (morpho)syntactic violation, in some cases it has been shown that L2 learners show an N400 component in response to a syntactic violation (Isel, 2007; Proverbio et al., 2002). This was taken as meaning that learners rely on lexical-semantic processing strategies in the first stages of L2 acquisition. Later studies (McLaughlin et al., 2010; Tanner et al., 2009) examined learners of German at the end of the first year of a formal course, and at learners at the end of the third year of a formal course. While the group of learners from the third year showed a P600 in response to morphosyntactic violations, the first year group showed a biphasic N400-P600 response. A further analysis showed that this biphasic N400-P600 response is not representative of all learners, but an artifact of averaging brain responses of all participants: the subgroup of participants with lower proficiency showed an N400 while the the subgroup with higher proficiency a P600. Moreover, the amplitude of P600 positively correlated with the discrimination scores of the judgment task. McLaughlin et al. (2010) reviewed more studies with this pattern and suggested that participants progress from a N400 to a P600 response, and that the response of each participant depends on the stage of grammatical learning.

1.5 Short-term language learning in adulthood

Recent electrophysiological studies have focused on changes that occur just after short periods of learning, mainly grammar and phonological learning (Zhang et al., 2000, 2001; Wang et al., 2003; Mueller et al., 2005, 2007, 2008; Davidson and Indefrey, 2009a,b, 2011) since they are known to be the subsystems which present more difficulties when learned in adulthood (Uylings, 2006). These studies select a small subset of grammar rules or phonological contrasts that are easy to learn within some hours of training (miniature languages), and train participants in the lab to study short-term language-learning related changes. A benefit of miniature-languages is that they enable better control over the learning process and the proficiency attained. Moreover, they enable better control over the to-be-learned properties with respect to the properties of the background languages.

Regarding phonological processing, Zhang et al. (2000, 2001) trained Japanese

native speakers to learn a sound contrast nonexistent in Japanese (r-l). The participants were trained for around 12 hours using visible articulation cues and MEG recordings were performed pre and post-training. During these recordings a magnetic signal component called the magnetic Mismatch Negativity (mMMN) was measured as an index of brain discrimination of the sounds. Behaviourally, participants improved over 20% on discriminating these sounds. Moreover, the mMMN component was localized in the auditory cortex, and changes in the mMMN component correlated with the behavioural changes.

Wang et al. (2003) examined brain changes in American English native speakers who were trained to acquire Mandarin Chinese tones. Participants were scanned in the MRI while they performed a tone detection task, before and after two weeks of training. Improvements in performance were associated with increased brain activity in left posterior temporal and left inferior-frontal areas.

Regarding grammar, short-term changes to violation-evoked components, in the time span of weeks or months, have also been seen during grammar learning using EEG. Davidson and Indefrey (2009a) studied how ERP components such as the P600 are related to the grammar acquisition process in adults using text materials. The results showed a P600-like effect during and following training for certain types of agreement violations in Dutch learners of German, similar to native German speakers. In a similar study, Davidson and Indefrey (2011) found P600 responses for both declension and gender violations using text materials. Davidson and Indefrey (2009b) studied the MEG signal and provided source correlates in response to phrase-order violations in German learners of Dutch. However, Davidson and Indefrey (2009b) examined the response to text-stimuli rather than auditory materials, and the grammar training was not carried out in the laboratory, but rather in a classroom in a longitudinal design. So it is not clear whether the the brain areas seen in that study would be seen in studies with a more focused laboratory-based training regime.

Other short-term learning studies have examined sensor-level violation effects with spoken materials. Unlike serially-presented text materials, spoken materials must be segmented during comprehension, and in principle this could modulate the timing of grammatical acquisition because learners may have difficulty recognizing individual lexical items because phonology also proves to be problematic for many learners. Mueller et al. (2005) showed that training can lead to the emergence of ERP grammatical violation patterns similar to native speakers with auditory materials, although with certain differences. In this study German participants were trained in a mini-version of Japanese (i.e., a small lexicon and a reduced set of rules) and tested on three types of grammatical violation (word category, case, and classifier violation). Participants completed a pretest, a training period using both comprehension and

production, and a final post-test. Trained participants reached high level proficiency over a period of four to ten hours in all the conditions, and native-like proficiency in two out of the three conditions (classifier and word category). For these two conditions a native-like P600 effect was observed after but not before training, but non-native speakers did not show an N400 effect that was present in the native speakers' response. A follow up study by Mueller et al. (2007) similarly found no differences in elicited P600 between native-speakers and trained learners. However, for learners the anterior negativity was found only in response to canonical sentences. Finally, Mueller et al. (2008) found that a group of participants trained with pseudoword materials showed a native-like N400-P600 response, suggesting that removing semantic load could free up resources for the processing of syntactic violations.

Relatively few training studies have examined how connected speech is produced in a second language during short-term learning. This is potentially an important omission in the literature because language learners usually acquire grammatical proficiency via practice of both comprehension and production (e.g. Mueller et al., 2005). Using MEG, Hultén et al. (2014) trained Finnish participants in a miniature language fragment of an artificial language. For the training phase (four days) participants saw a picture, and listened to and read a corresponding sentence, and finally had to repeat it. The task was arranged so that participants had to produce the correct agreement inflection on the last word of the sentences. They performed the experiment both in the miniature language (L2) and in the native Finnish (L1). The results showed that neural networks involved in production shared resources for L1 and L2. However, based on an increased amplitude response of left parietal cortex and angular gyrus in the novel language, Hultén et al. (2014) proposed that L2 speech production increased cognitive effort as compared to L1 language processing (see also Hanulová et al., 2011).

In summary, these kind of short-term learning designs allow us to measure brain changes while learning is taking place and give a new insight into language learning. All the studies mentioned in this section suggest that short-term plasticity due to language learning occurs and is measurable with non-invasive techniques. Nonetheless, these last mentioned EEG studies did not provide any source-correlates of learning. The anatomical correlates are important since modulations of these correlates during the tasks capture the short-term plasticity of cortical regions due to the learning process. These short-term plastic effects have been captured in other domains, i.e. motor learning tasks (Rossini and Melgari, 2011), but as shown in the introduction they are missing in the language learning literature. To the best of my knowledge, this thesis presents the first studies providing anatomical correlates of

short-term changes related to grammar and vocabulary learning, and the first study where training was carried out during MEG recordings.

1.6 Summary

This chapter described how brain plasticity can be understood on various spatial and temporal scales. In order to understand how brain changes occur due to language learning, it has been argued that a technique that measures entire-brain scale changes in a relatively short time is preferable. Therefore, this thesis employs MEG to investigate short-term language learning related plasticity. The basis of MEG data acquisition and data analysis is explained in Chapter 2.

Chapter 2

Measuring brain activity using Magnetoencephalography

The aim of this chapter is to introduce the type of activity recorded in the experiments of this thesis. In addition, principles of the MEG technique used for data acquisition, as well as the methods for data analysis are described.

2.1 Brain activity captured by MEG

Non-invasive brain measures of electrical or magnetic activity recorded with EEG or MEG have a bias to record certain types of activity from certain types of neurons.

Neurons communicate with one another by releasing neurotransmitters at synapses (Ramón y Cajal, 1904). The part of the neuron that sends the signal is called a pre-synaptic terminal, and the part of the neuron that receives the signal is called post-synaptic terminal. Membrane potential changes at this post-synaptic terminal are called post-synaptic potentials, and fluctuations of these potentials of large groups of neurons, when synchronized over time in the right physical arrangement (Lorente de No (1947)), will sum resulting in a current measurable with EEG or MEG (see Figure 2.1). When these fluctuations follow a rhythmic or repetitive pattern, they are called neural oscillations. In brain physiology these oscillations have been divided in bands according to the frequency of oscillation: delta band (1-4 Hz), theta band (4-8 Hz), alpha band (8-13 Hz), beta band (13-30 Hz) and gamma band (>30 Hz).

These oscillations become organized, amplified, and/or coupled during mental activity induced by a stimulus, thus giving rise to an 'evoked' (strongly locked to the stimulus/event) or 'induced' (weakly associated to the onset of a stimulus/event) rhythmicity. Evoked responses are usually measured by means of a time-locked

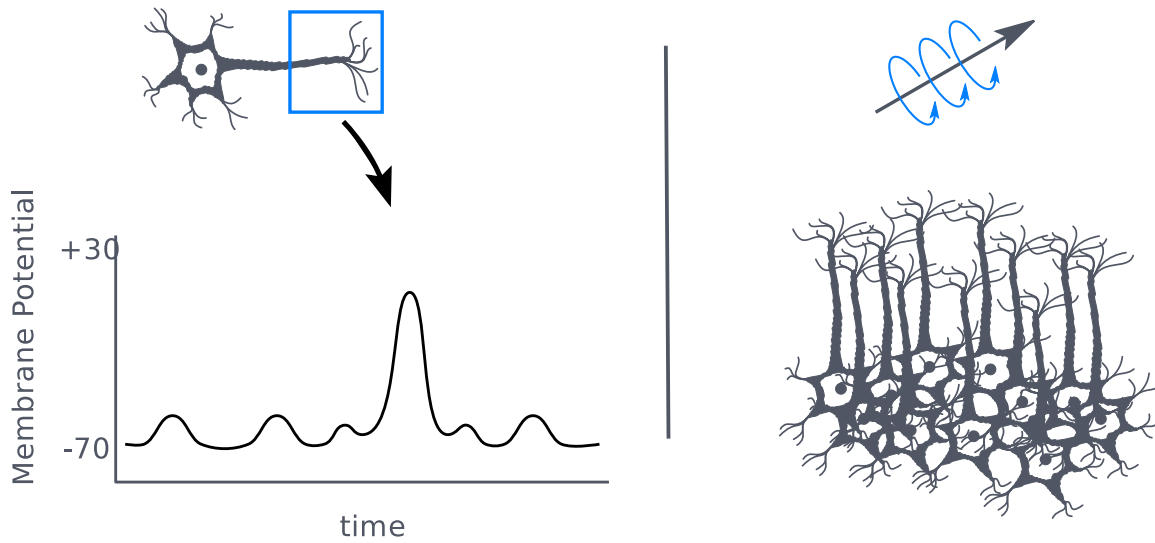


Figure 2.1: Post-synaptic signals. Left panel shows a post-synaptic membrane potential (grey) change of a single neuron. Right panel represents the measurable current (grey) and magnetic field (blue) originated by the post-synaptic potentials of a group of neurons.

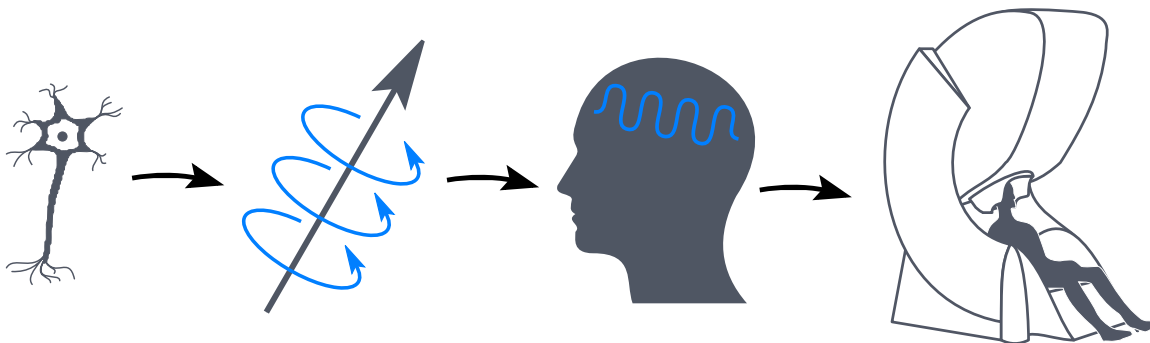


Figure 2.2: Schema of the signal captured by magnetoencephalography. From current generation (left) to signal measurement (right).

average response, resulting in the evoked response field (ERF) that is typically studied in MEG experiments or the evoked response potential (ERP) in EEG. In contrast, a time-frequency analysis is usually employed to study induced responses.

2.2 The basis of MEG

As with any electric current, the post-synaptic current will create a magnetic field around it which is proportional to the current. This field travels through the layers of the different brain tissues (gray, white matter, cerebrospinal fluid) the skull and the scalp and can be measured with the MEG sensors outside the head (see Figure 2.2).

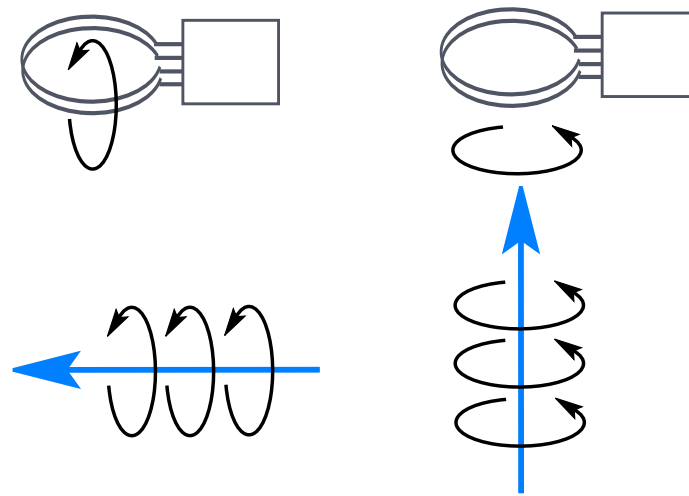


Figure 2.3: Magnetic fields of different currents. Left panel show an image of tangential current and how the corresponding field crosses an MEG sensor. Right panel show an image of a radial current and how the magnetic field does not cross the sensor.

The MEG sensors are rings of superconductive material. When a magnetic field crosses the rings, a small current proportional to the field is created and detected. A drawback of these sensors is that certain magnetic fields can not be detected, depending on the orientation of the neurons. Currents radial to the scalp create a magnetic field that do not cross the plane of the sensors, while currents tangential to the scalp do create measurable magnetic fields. Therefore, the tangential, but not the radial fields, can be measured with MEG (see Figure 2.3) (Hari, 1991).

Appropriate shielding of the MEG system is needed in order to perform the measurements. As shown in Figure 2.4, the magnetic field originating in the brain is of lower magnitude compared to the magnetic fields in the environment. If the MEG system is not adequately shielded, the sensors would also capture external magnetic fields and the signal of interest (the brain's magnetic fields) would become indistinguishable from noise. To avoid this, the MEG system is placed inside a shielded room which obstructs the magnetic fields of the environment to diminish their effect in the measurement area. Moreover, before all experimental sessions participants and experimenters are screened to ensure that additional noise sources are not introduced in the measurement area. In addition to noise reduction, the shielding room provides sound attenuating and creates a silent environment, which is important for studies using auditory stimuli.

The aim of data analysis is to reconstruct the approximate location and physical features of the electrical activity that produced the magnetic field measured at the sensors. This is, to understand which brain areas were involved in a given task and

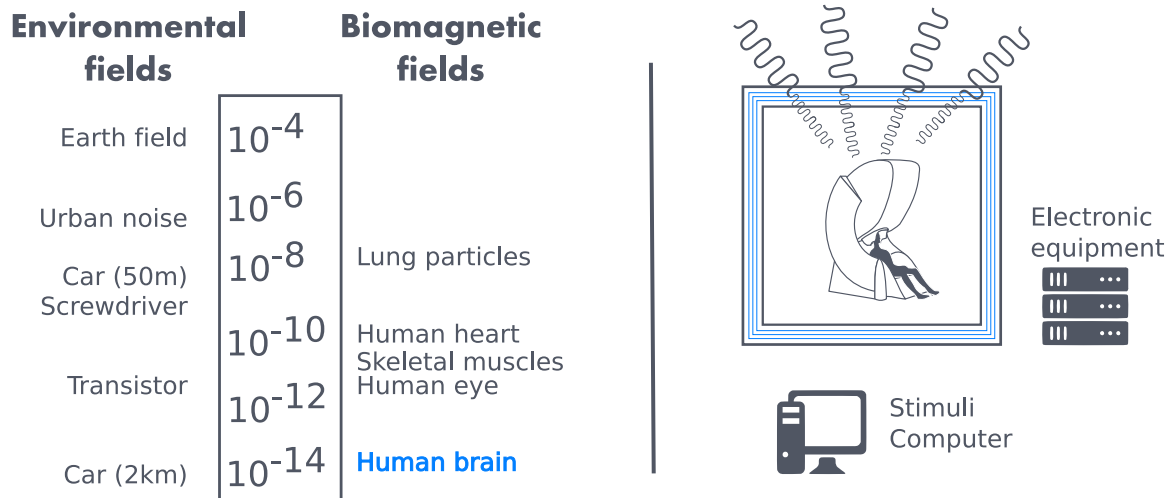


Figure 2.4: MEG signal and noise. Left panel indicates MEG signal amplitude compared to other source of magnetic signals (noise). Right panel illustrates an schematic of the shielding room used during MEG recordings to reduce this noise.

how the activity measured at these areas change depending on task manipulations.

2.3 Analysis of MEG data

This section explains the methods used to analyze the MEG data collected in the experiments of this thesis. The description of each analysis includes a section entitled 'How is this analysis reported in the Methods section?' which aims to illustrate an example of how each analysis is reported in the methods section of the experiments. Therefore, these paragraphs should be considered as a guide to interpret the methods section of the experimental chapters and not as a description of a common analysis performed in all the experiments, since each experiment has its own methods section with its individual analysis parameters.

The data of this thesis were collected using two different MEG systems: Elekta Neuromag (Elekta AB, Stockholm, Sweden) and CTF System (MISL, Coquitlam, Canada). The Neuromag system is composed of 306 sensors distributed in 102 locations. In each location one magnetometer and two orthogonal planar gradiometers are placed. In contrast, the CTF system is composed of 275 axial gradiometers. Axial gradiometers and magnetometers are suited to measure magnetic signals coming from deep brain, whereas planar gradiometers are appropriate to capture small magnitude magnetic signals. Each MEG system provides its own proprietary software for the noise reduction of the acquired data.

Data Pre-processing

Pre-processing steps are designed to isolate the data of interest for the analysis and discard those data that are not of interest (i.e., noise and known artifacts).

- Noise reduction. Despite the fact that data are recorded inside the shielded room, MEG data are still contaminated by considerable noise sources. Therefore, the MEG is used in conjunction with its own noise reduction software.

For the Elekta Neuromag system the software is called Maxfilter and cleans the data using a method called Signal Space Separation (SSS) (Taulu et al., 2005). This method uses the properties of electromagnetic signals and their fundamentals to separate the MEG data into three components: Signals with an origin inside the machine array (b_{in}), disturbances from outside the array (b_{out}) and noise generated close to the sensor array (b_s). The components related to disturbances are rejected. In this thesis the temporal expansion of this method is used (tSSS) where the component rejection is performed on a sliding window basis (Taulu and Simola, 2006). This enables the use of both spatial and temporal information to suppress the noise. The algorithm searches for high correlations between b_{in} and b_s components, which are indicative of artifacts. For that, the algorithm requires a set of parameters to set the length of the time window, the correlation threshold, the origin of the head and a list of noisy channels. After filtering, the head position is transformed to a single default position (0, 0, 40) across all participants so all the data comes from a comparable position for later analysis of sensor topographies.

For the CTF System, the system itself provides a 3rd-order gradiometer system. These gradiometers measurements together with the pre-processing package clean the data from the axial gradiometers, avoiding the need for the user to specify any parameter.

For both systems, along with the noise reduction algorithm, line frequency is eliminated (50 Hz), and data are downsampled to reduce computational effort. In this thesis downsampling and line frequency filtering are performed in separate steps.

How is it reported in the Methods section? (example for the Elekta Neuromag system)

Using MaxFilter 2.2, the recorded MEG data were filtered using temporal Source Space Separation (tSSS) with a X s time window and a minimum correlation of X . Individual's head origins and bad channels were supplied manually, data were downsampled to X Hz, and line frequency (50Hz) and its harmonics were filtered. Following recommendations from the MEG laboratory at MRC Cognition and Brain Sciences Unit ([http://imaging.mrc-cbu.cam.ac.uk/meg/Maxfilter V2.2](http://imaging.mrc-cbu.cam.ac.uk/meg/Maxfilter_V2.2)), the downsampling and the filtering were conducted in two separated steps in order to avoid a software bug which contaminates the data when these two steps are combined. Head origin of each participants was transformed to a default position to ensure that head position were standardized across participants and blocks, on average heads were shifted X mm ($std=X$).

- Epoching. The next step is usually to cut the data into segments of interest: epochs. The size of the epoch depends on the design of the experiment. However, it is common to cut the epochs in a way that also contains a period before the window of interest, known as the baseline. The baseline is used to compare activity prior to stimuli with the activity in response to the stimuli (i.e. 'active period') to study the dynamics of brain activity.
- Artifact rejection. This stage is applied such that epochs where the signal is mainly noise are detected and eliminated for further analysis. This can be done manually (visual screening) or automatically. When it is done automatically, data are standardized for the purpose of artifact rejection (for example, via a z -transform assuming the signal is a Gaussian process) and artifacts are rejected based on a threshold. The data remain in the original units for later analysis.
- Filtering. When prior knowledge of the frequencies that contain the activity of interest is available, data are filtered to keep only those frequencies. Zero padding at the edges of the epochs is advisable to avoid undesired edge effects after filtering. Three types of filters are used in this thesis and for each type of filter one or two cut-offs should be provided. Low-pass filters maintain the frequencies below the cut-off frequency, high-pass filters maintain the frequencies above the cut-off frequency and band-pass filters maintain frequencies between the two cut-offs (high and low frequencies).
- DC offset correction and detrending. A common next step is to eliminate the DC offset and/or the trend of the signal. The DC offset is the mean value of the signal. If epochs of different conditions have different DC offset, comparing

them directly could lead to erroneous results that claim signal differences (or lack of differences). To avoid this the mean value is subtracted from the original signal. This step is also referred to as demeaning. When the mean value is calculated using only the baseline, this step is called baseline correction. Also, linear trends in the signal due to large magnetic disturbances can be removed with a temporal detrending step.

These steps depend on the analysis that will be performed later on. For Time-Frequency analyses it is appropriate to eliminate both, as both the DC component and the linear trend leak into some time-frequency points (Fieldtrip Online Users Tutorial, 2013). For Event Related (ERF) analyses the decision is not clear. Baseline correction is usually performed to improve signal to noise. Regarding detrending, if the signal has late components that continue to the end of the epoch, detrending would eliminate those (real, evoked) effects or create new ones. However, if it is known that there is any artifact causing a drift in the signal, data detrending would be appropriate (Acunzo et al., 2012).

- Heart and eye-movement signal correction. Heart and eye-movements produce large electric and magnetic signals that contaminate the data. There are two common ways of rejecting these signals. First, artifacts showing clear heart or eye-movement effects can be visually identified and rejected. Second, suppressing heart and eye-movement components from epochs, instead of removing the whole trial, is preferable as rejecting too many trials would reduce the signal-to-noise ratio (SNR) of the data of subsequent analysis. If electrocardiogram (ECG) and electroculogram (VEOG and HEOG) data are available, an automatic identification of heart and eye-movement related effects can be carried out. For that, data are projected into a space where each component is independent to each other. This process is known as Independent Component Analysis (ICA, Vigário et al., 1998). Then, the independent components that exhibit higher correlation with the ECG and EOG signals are removed. Finally, the valid components are back-projected to the original space (sensor-space).

How is it reported in the Methods section?

The data were processed using the Fieldtrip toolbox (version 20141202 Oostenveld et al., 2011). The analysis was conducted only using the gradiometer sensors (the magnetometers were discarded due to noise reasons). First, data were segmented into epochs. The onset of the epoch was locked to the onset

of the trial. Data were segmented into X s epochs consisting of X s before the onset of the trial and X s following the onset of the trial. Then, the data were screened for jump artifacts and epochs with a z -value larger than X were automatically rejected. Each epoch was padded to X s and then filtered with a low-pass FIR filter at X Hz (one pass, zero-phase), and the resulting epochs were baseline corrected with respect to a X ms interval (X to X ms from trial onset). The data were decomposed using the fast Independent Component Analysis (fastICA) algorithm, where the number of components was equal to the number of gradiometers. No data dimension reduction algorithm was applied prior to the analysis. The fastICA algorithm was applied to uncombined gradiometers (X sensors). Then, the correlation of each ICA component time-course with the HEOG, VEOG, and ECG time-course was calculated and the components whose correlation exceeded X standard deviations of the mean correlation in any of the cases (HEOG, VEOG or ECG) were removed before backprojecting the single-trial data into the original sensor space.

Time-locked analysis

The response to a single stimulus available in each epoch is very noisy and difficult to characterize. In practice, epochs that contain responses to a common feature (epochs from the same condition) are averaged together as a group in order to improve signal-to-noise ratio (SNR). The assumption is that the effect of interest is time- and phase-locked to stimulus presentation (i.e., it is an evoked response). As a result, averaging the epochs reduces the noise (which is assumed to be independent of the stimuli) and make clearer the time and phase locked effect. When this analysis is applied to MEG data, the averaged signal is called an Event-Related Field (ERF), analogous to the Event-Related Potential (ERP) obtained from averaging EEG epochs. In general, the methods description should indicate to which time point of the trial are the epochs locked. In addition, it is necessary to specify which epochs have been averaged together (all the epochs of these condition, only the epochs which correspond to a correct answer, the ones belonging to two conditions, etc.) as well as the sensors included in the analysis. Afterwards, an optional step is to combine the planar gradiometers, where the horizontal and the vertical gradient of planar gradiometers are combined using Pythagoras rule. When combined planar gradiometers are visualized, the evoked fields show a peak on top of the source.

Usually ERFs of different conditions are represented in a common graph where the X axis denotes the time dimension of the (average) trial and the Y axis is the ERF magnetic field magnitude (see Figure 2.5). When the magnitude is squared magnetic field per area, measured in units of $(\text{fT}/\text{cm})^2$, the figure is showing combined

Event Related Analysis (ERF)

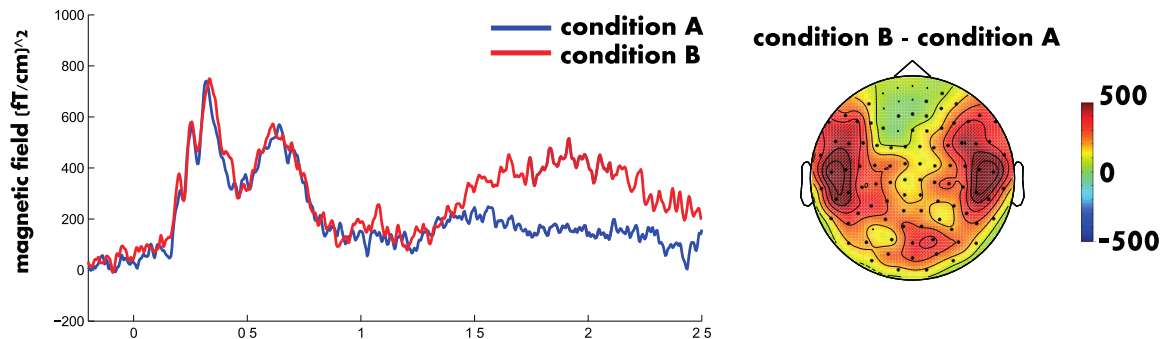


Figure 2.5: Example of a time-locked analysis result report.

gradiometers, whereas when it is a magnetic field gradient, measured in units of (fT/cm), it is showing uncombined gradiometers. An ERF plot is usually accompanied by a topoplot. A topoplot is a plot that represents the topographic distribution of the ERF over the MEG sensors during a given time window. A topoplot can also display the topographic distribution of the differences of the ERFs during a given time window (see Figure 2.5). Topography maps show in a broad sense the spatial location of the effects (anterior, posterior, left hemisphere, right hemisphere). Moreover, topography maps can be used to validate source level results since source reconstruction should give results coherent with the topography maps (i.e., if a topography map shows the effect in right anterior sensors, it is suspicious if the source reconstruction localizes the effect in left posterior areas).

How is it reported in the Methods section?

The uncombined gradiometers were then averaged according to experimental condition (violation vs. control). Only trials associated with correct behavioral responses were included in the violation control ERF contrasts. Once averages were calculated, the planar gradiometers were combined.

Time-Frequency analysis

Although time-locked analysis is an appropriate method to study event related evoked fields, not all brain responses are tightly time- and phase- locked to the stimuli (induced activity). Induced oscillations can be defined as the loose modulation of ongoing brain activity due to an event. If induced responses are time-locked averaged they may cancel each other, since they may exhibit different phases across trials. Time-frequency analysis is used to study these oscillations, which consists in examining how the short-time power-spectrum of the signal changes over time.

Time Frequency Analysis

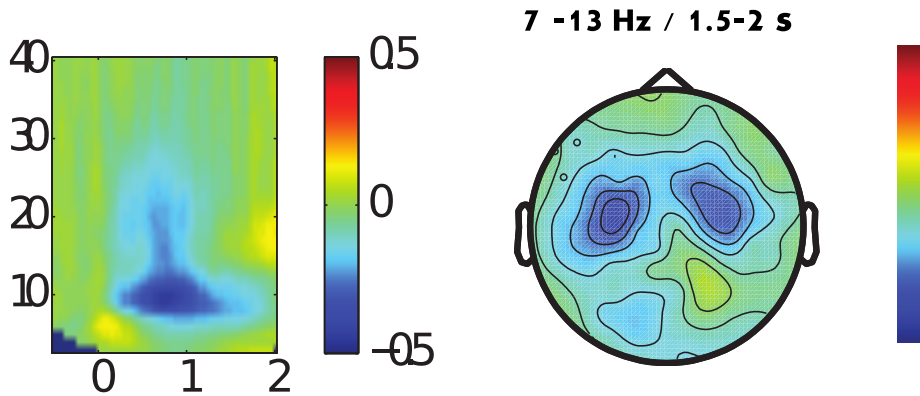


Figure 2.6: Example of a time-frequency analysis result report.

There are various mathematical approaches to obtain this. The one used in this thesis involves the Hanning taper. In this approach, the time frequency representation of the power is calculated using a sliding window where data are multiplied by a Hanning taper in order to reduce spectral leakage and control the amount of frequency smoothing. In order to improve the temporal resolution, a window whose length is dependent on the frequency (e.g., a given number of cycles) is used. The higher the frequency the smaller the time window and the higher the temporal resolution. Nonetheless, this is at the cost of frequency smoothing and reporting the resulting smoothing is important. It is necessary to indicate the number of cycles potentially present in the length of time-window used, as well as the time-step of the window transition. To avoid cancelling the non-phase locked responses, the time-frequency representations are calculated for each trial and then averaged across trials.

The results of time-frequency analysis are shown as a color map where the X-axis represents time, the Y-axis represents frequency and the color scale represents the power change relative to the baseline interval (see Figure 2.6). This time frequency plot can be accompanied by a topographic plot that represents the power of a frequency range for a given time window of interest.

How is it reported in the Methods section?

Oscillatory power of the retrieval phase was examined using a single Hanning taper based on frequency dependent window length. Six cycles per time window were used, which was sliced in steps of X s. The analysis was performed in the whole trial (between -X and X s) and between X and X Hz in steps of X Hz. This

resulted in linearly-variant frequency smoothing of X Hz at X Hz. Power changes were calculated relative to a baseline ($-X - X$ s) such that changes from the baseline in the time interval following the word were normalized by the baseline (e.g., 'relative change').

Source level analysis

One of the main advantage of MEG is that it that allows the localization of candidate brain sources for brain activity. In order to achieve source localization a forward model (or leadfield) must be defined that describes how activity generated in a single location in the brain would be reflected in the sensor space. To calculate the forward model the brain is segmented into the different tissues (scalp, skull,...) and a specific conductivity value is assigned to each of them. Multiple forward models have been described in the literature. In this thesis the single shell approximation (Nolte, 2003) will be used. Moreover, a set of locations (e.g. within a spatial grid) must be specified. Based on the forward model, the inverse model/solution is calculated for given data to obtain an estimate of the sources that potentially gave rise to the measurements. There are several algorithms to compute the inverse solution. In the following, the ones used in the thesis are briefly described.

The **Minimum Norm Estimation** (MNE, Hämäläinen and Ilmoniemi, 1994) is a source-reconstruction method that applies estimation theory to the problem of calculating the distributed currents in the brain. Essentially there is no prior assumption except that source currents are confined to a certain region, in this case, the brain. The estimate is the shortest vector in the source-current space, i.e., the source distribution with minimum overall energy that can explain the measured signals. Among the different source reconstruction methods, this approach is commonly employed to analyze evoked responses and to track wide-spread brain activity over time. The MNE version used in this thesis is the one implemented in fieldtrip (Dale et al., 2000).

How is it reported in the Methods section?

For the source level data analysis, the Minimum Norm Estimate (MNE) approach (Dale et al., 2000) was used. Structural MRI (T1 images) were segmented into scalp, skull brain and CSF, and a volume conduction model was constructed based on this segmentation using a single shell approximation (Nolte, 2003) by assigning a conductivity value to the brain. This volume conduction model and a X-point mesh grid based on the canonical cortical sheet (available in Fieldtrip) were used to construct the leadfields. These leadfields were pre-whitened before calculating the inverse solution. When the source covariance is estimated a scaling factor is

*applied (calculated automatically by Fieldtrip) in order to force the source covariance to fulfill that $\text{trace}(A^*R^*A')/\text{trace}(C)=1$ where A is the leadfield matrix, R is the source covariance matrix and C is the noise covariance matrix. The time courses for each mesh-vertex in the forward model was estimated using MNE with a regularization parameter of three (for both lambda and lambda noise). After that, the three moments of the source time series were projected to their strongest orientation at each vertex.*

The **Minimum Variance distortion-less response** (MVDR, Van Veen et al., 1997, commonly known as Beamformer) is a method imported from the field of signal processing and adapted for the neuroimaging domain. For each spatial location, linearly constrained minimum variance (LCMV) filters are designed which pass brain electrical activity from a specified location while attenuating activity originating at other locations. The spatial filters are calculated minimizing the trace of the sensor level covariance matrix C subject to $W^T A = I$, where W is the filter matrix and A is the leadfield matrix. Among the different source reconstruction methods, beamformer is ideally-suited for the localisation of induced, or non-phase-locked, changes in on-going cortical oscillatory rhythms (Brookes et al., 2008).

How it is reported in the Methods section?

A beamformer spatial filtering approach was employed. For that, a data covariance matrix within a 1- to 150-Hz frequency window and a time window spanning the whole experiment was calculated. Regularization was applied using the Tikhonov method with a regularization parameter equal to 5% of the maximum eigenvalue of the unregularized matrix. Spatial locations were defined at vertices of a regular (X mm) grid spanning the whole brain volume and a forward model was constructed based on a dipole approximation and a multiple local sphere head model (Huang et al., 1999). Weights for the broad band (X - X Hz) signal at each voxel were derived.

Statistical analysis

Statistical analysis is performed to study the consistency and meaningfulness of the results' patterns across participants and the differences across conditions, in order to isolate or highlight a given modulation of brain activity. A main confound in neuroimaging is the multiple comparison problem. When a large number of statistical tests is performed, the probability of obtaining false-positives increases. Therefore, a correction procedure is needed to reduce the risk of the false-positives, without increasing false-negatives. Among all the possible corrections available in the literature for MEG, random cluster permutation was used in this thesis.

Random cluster permutation (Maris and Oostenveld, 2007) is a non-parametric approach that makes limited assumptions about the probability distributions of the variables being assessed. At first, a classical parametric test (i.e. t-test) is performed on all data points under the null hypothesis. Clusters of statistically significant points are formed based on proximity and for each cluster a statistical index (named clusterstat) is obtained by adding all the values of the cluster. Then, in each randomization the same procedure is repeated, with subjects randomized. A distribution with the maximum clusterstat value at each randomization is computed. Finally, the clusterstat of the original comparison is contrasted with this distribution to assess the statistical significance of the original test.

How is it reported in the Methods section?

Statistical differences between conditions were assessed using a clustering and randomization test (Maris and Oostenveld, 2007). A randomization distribution of cluster statistics was constructed for each subject over time and sensors and used to evaluate whether there were statistically significant differences between conditions over participants for each violation-control comparison in a phase of training (e.g., pre-test, training, post-test, etc.). In particular, t-statistics were computed for each sensor and time point during the [-X X] time window, and a clustering algorithm formed groups of channels over time points based on these tests. The neighborhood definition was based on the template for combined gradiometers of the Neuromag-306 provided by the toolbox. In order to a data point to become part of a cluster, they were thresholded at $p=0.05$ (based on a two-tailed dependent t-test, using probability correction) and it had to have at least two neighbours also in the cluster. The sum of the t-statistics in a sensor group was then used as a cluster-level statistic (e.g., the maxsum option in Fieldtrip), which is then tested using a randomization test using X runs.

2.4 Summary

This chapter described how the magnetic field originated by postsynaptic activity is measured by MEG. Moreover, the methods for data analysis that are used in Chapters 3,4,5 have been explained.

Part II

Experimental Section

Chapter 3

Grammar learning experiment

3.1 Rationale

In this chapter we report a source reconstruction experiment of evoked brain activity recorded using MEG before, during and after a few hours of grammar learning in adult Spanish (Spanish (SP), L1) learners of Basque (Basque (BQ), L2) with the goal of better characterizing the areas involved in the ability to recognize grammatical constraints.

According to Mueller et al. (2008), reducing semantic load can free up resources for the processing of syntactic violations. Therefore, Spanish learners were presented spoken phrases that used nouns and adjectives that were Basque-Spanish cognates in order to reduce the lexical-semantic or phonological learning load and enable participants to segment the speech during learning. Notably, Spanish and Basque share most of their phonological segmental inventories, despite substantial differences in their grammatical systems.

In naturalistic environments language learners acquire grammatical proficiency via practice of both comprehension and production. To better mimic the learning task usually involved in grammar learning, learners discriminated between grammatically-correct and -incorrect phrases, as well as learned to produce the correct form of the phrases in a picture-description task. Also, instead of comparing L2 learners to a separate group of native speakers (as in Mueller's studies), following Hultén et al.'s (2015) approach, the response in both L1 and L2 of the same participants were measured to better characterize the difference in response to the two languages.

Our main hypothesis is that when using cognate vocabulary grammatical rules can be incorporated rapidly. Neurophysiologically, the hypothesis is that the brain

networks that form the basis for L1 proficiency are engaged during the explicit learning of a new L2. The main prediction based on this is that once the learned rule has been incorporated into real-time language processing, left posterior areas - which show a greater amplitude evoked response to a grammatical violation in the L1 - will also be the areas that exhibit a greater amplitude violation response in the L2. Nevertheless, as initial stages of L2 learning remain unstudied with MEG, it is not appropriate to assume the areas involved in the task and restrict our analysis to those.

3.2 Material and Methods

Ethics Statement

The study was carried out at the Basque Center for Cognition, Brain and Language, and it was approved by its institutional review board.

Participants

Participants were 17 (9 female, 8 male) healthy, right-handed Spanish native speakers with no knowledge of Basque, with no hearing or reading disorders. The participants were recruited from Donostia-San Sebastian or the surrounding areas. All participants were screened for magnetic interference prior to data collection, and provided informed consent (Declaration of Helsinki) before starting the experiment. Additional data from two subjects were recorded, but the data were discarded from the analysis because the participants did not follow the instructions.

Experiment

For this study we used a small fragment of Basque, which we will term 'mini-Basque'. The fact that Spanish and Basque share a relatively large proportion of their vocabularies, but differ substantially with respect to grammar was exploited. For the stimuli, Basque noun phrases that would contain new grammar rules for the participants but did not require learning new words were constructed, as the words were chosen to be already familiar to the subjects from their Spanish. In total, we chose 80 nouns and four adjectives that are phonologically similar to Spanish (Phonological description Levensthein distance mean=0.77, standard deviation=1.4 phonemes). Also, the selected grammatical relation (number marking) is relatively simple for participants to learn in the span of a few experimental sessions. Grammatical number is marked in both languages, but is implemented in a different way in Basque due to the different head directionality and the phrase ordering.

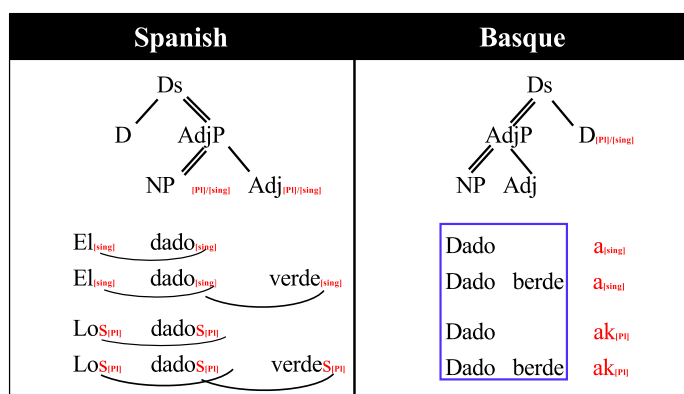


Figure 3.1: Grammatical rule differences between Spanish and Basque number inflection for noun phrases. dado: die, verde/berde: green, el/los/a/ak: the, D: determiner, DS: determiner structure, Adj: adjective, AdjP: adjective phrase, NP: noun phrase, Sng: singular, Pl: plural. Arrows indicate marking relationship, thin lines dependency, double lines head dependency. See Table 3.1 for a translation.

In terms of the classification used by Caffarra et al. (2015), number inflection is implemented 'differently'. As described in Figure 3.1, Spanish constructs plural determiner phrases marking the number in all the elements of the phrase. On the other hand, Basque only marks number on the last element of the phrase.

Stimuli

The experiment included three types of noun phrases: control phrases, violation phrases, and fillers (See Table 3.1).

As can be seen from both Figure 3.1 and Table 3.1, number agreement in Spanish is marked by inflecting all the elements of the noun phrase: the determiner, the noun and the adjective: Los dados verdes (the green dice). The Spanish violation phrases were created by marking an incorrect number inflection of the adjective, therefore, the violation/control critical points come near to the end of the adjective. In contrast, number agreement in Basque is indicated only at the last word of the phrase (in this case, it could be the adjective or the noun): Dado berdeak (the green dice). The critical morpheme for the violation phrases is the first morpheme of the following adjective because it indicates the adjective follows an inflected noun. We also added a filler condition consisting of simple noun phrases in Basque so that participants could not simply detect violations only on the basis of an inflected noun. In this case the noun phrases were composed of a noun, determiner, and number inflection, but no adjective. This obliges the participants to wait and listen if any adjective follows the marked noun before deciding if it is a correct or incorrect phrase. In

Condition	Mini-Basque Phrases	Spanish Phrases
Control phrases	Dado[] berdea[Sing] <i>The green die</i>	El[Sing] dado[Sing] verde [Sing] <i>The green die</i>
	Dado[] berdeak[Pl] <i>The green dice</i>	Los[Pl] dados[Pl] verde s[Pl] <i>The green dice</i>
Violation phrases	*Dadoa[Sing] berdea[Sing] <i>*The green die</i>	*El[Sing] dado[Sing] verde s[Pl] <i>*The green die</i>
	*Dadoak[Pl] berdeak[Pl] <i>*The green dice</i>	*Los[Pl] dados[Pl] verde [Sing] <i>*The green dice</i>
Fillers	Dadoa[Sing] <i>The die</i>	El[Sing] dado[Sing] <i>The die</i>
	Dadoak[Pl] <i>The dice</i>	Los[Pl] dados[Pl] <i>The dice</i>

Table 3.1: Example phrases. | denotes the violation point and the corresponding control point. Feature marking is shown in brackets (e.g., [Pl] or [Sing]), with underspecification in empty brackets: [].

Basque, the determiner is not optional, so no trials consisting of a bare noun (e.g., *dado*) were presented. Trials from the filler condition were not included in the electrophysiological analysis.

Each of the comprehension test/training blocks consisted of 184 trials: 80 control phrases, 80 violation phrases, and 24 fillers. Violation, control and filler phrases were randomized inside each block, but the same list was presented for all participants. Each block lasted approximately 15 minutes.

The phrases of mini-Basque consisted of 80 nouns and four adjectives chosen to be phonetically similar to Spanish words. Sixty of these nouns and two adjectives were used for the training blocks and the remaining 20 nouns and two adjectives were used in the generalization blocks. Thus, the same phrase was never heard twice, and the words that were used in training blocks were not present in the generalization tests.

Stimuli were recorded in a sound-proof booth by a native female Spanish-Basque bilingual. The amplitude of the resulting audio files were equalized to the same loudness and presented to participants at 65 Db. The length of the recorded stimuli per block and condition can be found in Table 3.2.

Block	Control	Violation
Pre-Test BQ	1.32(0.23)	1.48(0.29)
Pre-Test SP	1.56(0.29)	1.61(0.26)
Training 1	1.42(0.32)	1.54(0.34)
Training 2	1.43(0.29)	1.60(0.38)
Training 3	1.41(0.28)	1.58(0.36)
Gen-Test BQ	1.43(0.25)	1.58(0.31)
Post-Test SP	1.61(0.29)	1.65(0.35)

Table 3.2: Mean (std) length (in seconds) of stimuli per block and condition.

Because the stimuli were presented auditorily, the time point for each trial's critical morpheme varied. In order to establish the critical point, we calculated the average critical point for Spanish and Basque separately. For Basque we measured the onset of the second word using the software Praat (Boersma and Weenik, 1990, version 5326), and then the values were averaged. For the Spanish, the offset of the last word was measured (also using Praat), and then the values were averaged.

During MEG recordings the auditory stimuli were presented via panel speakers (two SSHP 60 x 60 panels; Panphonics Oy, Helsinki, Finland).

Design and Tasks

The study was carried out in two experimental sessions conducted on two consecutive days. There were two main reasons to go for a two-day design. First, to test whether any effects seen on the first day remain until the second session. Second, in order to study the evolution of brain responses during training, a substantial number of trials are needed. If all were presented in the same session, the experiment would become too long and tiresome for the participants. The first session included seven blocks: a pretest in Basque, a pretest in Spanish, rule explanation, training on comprehension, training on production, training on comprehension again, and training on production again (see Figure 3.2, column 1).

The comprehension tasks consisted of a series of trials in which a fixation cross appeared for two seconds on a back-projection screen, followed by the presentation

of the auditory sentence via the panel speakers. The fixation cross remained on screen during the playback, and following the termination of a phrase, a question prompt appeared on the screen, and remained onscreen until the participant's response or a time out (four seconds). During training blocks, the response was followed by a feedback display consisting of a green (correct) or red (incorrect) square. If a participant responded more than once, feedback was provided based on the first response and the rest were discarded.

The pretest in Basque was conducted to confirm that participants' knowledge of Basque was minimal, and to measure whether there were any physiological effects due to stimulus differences between conditions. In the pretest, participants were told that they would hear Basque phrases and that they were to indicate if the phrases they heard were correct in Basque or not by pressing a green or red button, respectively. The Spanish pretest was conducted in order to measure a baseline response in the participants' L1 that would allow later comparisons with Basque blocks. In this part, participants were instructed to indicate if the phrase they heard (in Spanish) was correct or incorrect, again by pressing a green or red button. Participants did not receive feedback in any of the pretest blocks. After both pretests were completed, participants were told that the remainder of the study consisted of a rule-learning task in Basque. In order to explain the rule the example of Figure 3.1 was used. Participants were allowed to ask as many questions as they wanted to ensure they understood the rule. Following the rule explanation and an explanation of the task, the training phase in the MEG started. For the comprehension blocks, participants listened to the Basque phrases and had to decide if the phrase was correct or incorrect, just as in the pretest. However, unlike the pretest, on each trial participants got visual feedback.

The production task consisted of a picture description task. Participants first saw a fixation cross for two seconds, followed by an image with either one or two drawings presented in one color (e.g., a single green die, or a pair of green dice) on the back-projection screen for three seconds. After the image, a question mark prompt appeared for seven seconds, and participants produced either a singular or a plural noun phrase. They received visual feedback and then the following trial began. If a participant responded more than once, feedback was provided based on the first response and the rest were discarded. The production tasks on the training blocks were done in Basque.

The second session included six components: (1) training in comprehension, (2) training in production, (3) generalization test in comprehension, (4) generalization test in production, (5) comprehension test in Spanish, and (5) a production test in Spanish (see Figure 3.2, column 2). The training blocks were presented in the

same sequence as the previous day. For both the generalization comprehension and generalization production tests in Basque, the same structure and instructions were used as in the training blocks, but no feedback was provided. Moreover, the stimuli used (explained in the previous section) were different from the stimuli used in training. The aim of the generalization blocks was to assess whether participants had learned to apply the grammar rule to new words rather than memorizing that particular noun-phrases were correct or incorrect. The Spanish comprehension and production blocks were completed to have a baseline in L1 for both production and comprehension for further comparison with Basque.

Procedure

The two sessions were recorded on two consecutive days. All the blocks described in the design section were recorded for each participant. During the recordings, participants were asked to relax and acquire a comfortable position between blocks in order to prevent movements during data acquisition; they were instructed to avoid head, body and eye movements during the task. Two (vertical and horizontal) EOG channels were recorded for later artifact rejection, and a single bipolar ECG lead was recorded for heartbeat removal by ICA.

A Polhemus Isotrak (Polhemus, Colchester, VM, USA) was used to digitize the head shape (around 120 points for each subject) and the fiducials in order to be able to align the head to each subject's structural MRI (T1 image). Additionally, five head localization coils were attached to the participant's head, and their spatial location (relative to fiducials) was recorded. The five coils were active during the MEG recording to provide continuous head position information (cHPI). The MEG data were acquired with a 1000 Hz sampling rate and filtered during recording with a high-pass cutoff at 0.03 Hz and a low-pass cutoff at 330 Hz via the Elekta acquisition software.

Data Analysis

Behavioural Analysis

The behavioral response data corresponding to comprehension blocks were modeled using a multilevel generalized linear regression model (Dixon, 2008) using the factors condition (violation vs control) and block (e.g. pre-test, training 1,...). The coefficients from the multilevel analysis are hard to interpret directly, therefore, they were back-transformed to proportions of correctness. The data from the production blocks were similarly modeled using a multilevel generalized linear regression model

DAY 1		DAY 2											
	Pre-Training Test (Basque) - Judgement task - No feedback		Pre-Training Test (Spanish) - Judgement task - No feedback										
	Rule Explanation		Training 3 (Basque) - Judgement task - Visual feedback										
<table border="1"> <thead> <tr> <th>Spanish</th> <th>Basque</th> </tr> </thead> <tbody> <tr> <td>El dato verde.</td> <td>Dato berde.</td> </tr> <tr> <td>El dato verde.</td> <td>Dato berde.</td> </tr> <tr> <td>Los datos verdes.</td> <td>Dato berde.</td> </tr> <tr> <td>Los datos verdes.</td> <td>Dato berde.</td> </tr> </tbody> </table>	Spanish	Basque	El dato verde.	Dato berde.	El dato verde.	Dato berde.	Los datos verdes.	Dato berde.	Los datos verdes.	Dato berde.			Training 3 (Basque) - Picture naming - Visual feedback
Spanish	Basque												
El dato verde.	Dato berde.												
El dato verde.	Dato berde.												
Los datos verdes.	Dato berde.												
Los datos verdes.	Dato berde.												
	Training 1 (Basque) - Judgement task - Visual feedback		Generalization Test (Basque) - Judgement task - No feedback										
	Training 1 (Basque) - Picture naming - Visual feedback		Generalization Test (Basque) - Picture naming - No feedback										
	Training 2 (Basque) - Judgement task - Visual feedback		Post-Training Test (Spanish) - Judgement task - No feedback										
	Training 2 (Basque) - Picture naming - Visual feedback		Post-Training Test (Spanish) - Picture naming - No feedback										

Figure 3.2: Design of the study. The left column contains the tasks of the first session and the right column shows the tasks of the second session (Session 1 and 2 were conducted on consecutive days). Dark grey blocks are comprehension blocks (grammaticality judgement task). White blocks are production blocks (picture naming task), and the light grey block is the grammar rule explanation.

(Dixon, 2008) using the factor block (e.g. pre-test, training 1,...). The aim of this study is to examine the grammar acquisition and not the lexical acquisition. Therefore, a response was considered correct when the grammar rule was correctly applied even if the intonation, pronunciation of the noun or the adjective was not completely correct. For example, if participants used the Spanish form of the cognate but the Basque grammatical rule, the response was considered correct, with respect to grammar.

MEG data

The design contained both comprehension and production tasks. In order to show that participants acquired the rule correctly behavioural analysis, we report results from both type of tasks. Nevertheless, the interest of the study is mainly on the discrimination of grammatical correctness of the sentences. Therefore, for the MEG, data only the comprehension tasks were analyzed.

Using MaxFilter 2.2, the recorded MEG data were filtered using temporal Source Space Separation (tSSS) with a four second time window and a minimum correlation of 0.98. Each individual's head origins and bad channels were supplied manually, data were downsampled to 250 Hz, and line frequency (50 Hz) and its harmonics were filtered. Following recommendations from the MEG laboratory at the MRC Cognition and Brain Sciences Unit (http://imaging.mrc-cbu.cam.ac.uk/meg/Maxfilter_v2.2), the downsampling and the filtering were conducted in two separated steps in order to avoid a software bug which contaminates the data when these two steps are combined. Head origin of each participant was transformed to the default position, to ensure that head position was standardized across participants and blocks. On average, heads were shifted 20.4mm (std = 6.65) on the first day and 22.8mm (std = 5.01) on the second day. The data were processed using the Fieldtrip toolbox (version 20141202, Oostenveld et al., 2011), and all the analysis were conducted only using the gradiometer sensors (the magnetometers were discarded due to noise reasons). First, data were segmented into epochs. The onset of the epoch was locked to the onset of the trial for both Basque and Spanish. Data were segmented into four second epochs consisting of one second before the onset of the trial and three seconds following the onset of the trial.

Then, the data were screened for jump artifacts: epochs with a z-value larger than 20 were automatically rejected. Each epoch was padded to 12 seconds and then filtered with a low-pass FIR filter at 40 Hz (one pass zero-phase), and the resulting epochs were baseline corrected with respect to a 200 ms interval (-200 - 0 ms from trial onset).

The data were decomposed using the fast Independent Component Analysis (fast ICA) algorithm, the number of components that were calculated was equal the number of gradiometers (204), and prior to the analysis no data dimension reduction algorithm was applied. The fastICA algorithm was applied to uncombined gradiometers (204 sensors). Then, the correlation of each ICA component time-course with the HEOG, VEOG, and ECG time-course was calculated. The components whose correlation exceeded three standard deviations of the mean correlation in any of the cases (HEOG, VEOG, or ECG) were zeroed out before back projecting the single-trial data into the original sensor space.

Time-locked analysis

The uncombined gradiometers were then averaged according to experimental condition (violation vs. control). Once averages were calculated, the planar gradiometers were combined. Only trials associated with correct behavioral responses were included in the violation control event related fields (ERF) contrasts, except for the Basque pre-test. In this block participants had few correct trials and in order to have sufficient SNR all clean trials were included (average number of included trials per block are provided in Table 3.3).

The differences between conditions were assessed using a clustering and randomization test (Maris and Oostenveld, 2007). A randomization distribution of cluster statistics was constructed for each subject over time and sensors and used to evaluate whether there were statistically significant differences between conditions over participants for each violation-control comparison in a phase of training (e.g., pre-test, training, post-test, etc.). In particular, t-statistics were computed for each sensor and time point during the [-0.2 2.5] time window, and a clustering algorithm formed groups of channels over time points based on these tests. The neighborhood definition was based on the template for combined gradiometers of the Neuromag-306 provided by the toolbox. In order for a data point to become part of a cluster, the point was thresholded at $p < 0.05$ (based on a two-tailed dependent t-test, using probability correction) and it had to have at least two neighbours. The sum of the t-statistics in a sensor group was then used as a cluster-level statistic (e.g., the maxsum option in Fieldtrip), which is then tested using a randomization test using 1000 runs.

For simplicity, the visualization of the results shows the ERF waveforms of all sensors, and the topography plots show the raw average of the violation-control difference of the statistically most significant cluster. If a sensor was part of the cluster during any point of the window (not necessarily the whole time window), it appears highlighted on the topography plot.

Block	Control	Violation
Pre-test BQ	77.8 (1.99)	78.7 (1.8)
Pre-Test SP	73.2 (7)	73.2 (7.4)
Training 1	72.8 (4.7)	70.5 (7.2)
Training 2	69.9 (18.5)	69.9 (18.7)
Training 3	76.4 (3.7)	72.7 (10.8)
Gen-test BQ	74.8 (3.6)	72.4 (6.6)
Post-test SP	73.8 (4.5)	69.1 (14.6)

Table 3.3: Mean (std) number of trials included in the MEG analysis of the comprehension tasks per block.

Source level analysis

Minimum Norm Estimate (MNE) (Dale et al., 2000) was used. Structural MRI (T1 images) were segmented into scalp, skull brain and CSF, and a volume conduction model was constructed based on this segmentation using a single shell approximation (Nolte, 2003) by assigning conductivity to the brain. This volume conduction model and a 5124-point mesh grid based on the canonical cortical sheet (available in Fieldtrip) were used to construct the leadfields. These leadfields were pre-whitened before calculating the inverse solution. When the source covariance is estimated a scaling factor is applied (calculated automatically by Fieldtrip) in order to force the source covariance to fulfill the following equation: $\text{trace}(A^*R^*Aff)/\text{trace}(C)=1$ where A is the leadfield, R is the source covariance and C is the noise covariance. The time courses for each mesh-vertex in the forward model was estimated using MNE with a regularization lambda value of three (for both lambda and lambda noise). After that, the three moments of the source time series were projected to their strongest orientation at each vertex.

Time-constrained statistical analysis

Statistical analyses were also conducted on the source level data to identify which areas contributed to the differences seen at the sensor level. In source space, a clustering and randomization test (500 runs) was used, similar to the sensor level analysis (Maris and Oostenveld, 2007). In particular, t-statistics were computed for each vertex and on an averaged time window selected for each block based on

sensor level-analysis, and a clustering algorithm formed groups of vertices based on these tests. The neighbourhood was defined based on a distance measure (maximum neighbour distance of 10). In order for a data point to become part of a cluster, it was thresholded at $p < 0.05$ (based on a two-tailed dependent t-test, using probability correction) and it had to have at least 2 neighbours. The sum of the t-statistics in a sensor group was then used as a cluster-level statistic (e.g., the `ffmaxsumff` option in Fieldtrip), which is then tested using a randomization test using 500 runs. In order to simplify the visualization of the source-space we only show the regions that were statistically significant or close to significant. For the blocks with no significant cluster the cluster with the lowest p-value is shown in order to show the trend of the data in that block. However, we are aware that the interpretation of these no-significant clusters should be cautious. The cortical regions' labels were defined based on the AAL atlas provided in the Fieldtrip toolbox: first the AAL atlas defined in the MNI space was interpolated to the common source mesh. Then a mask was created for each significant cluster and the labels of the masked vertex were obtained from the interpolated atlas.

Unconstrained statistical analysis

Another statistical analysis of the source space, without restricting it to a given time window, was conducted. While the previous analysis would identify the sources responsible for the effects picked at sensor level, this second analysis explores any violation-control effect at source level that may have not been picked at sensor level.

For this unrestricted analysis, a clustering and randomization test (500 runs) was used, similar to the sensor level analysis (Maris and Oostenveld, 2007). In particular, t-statistics were computed for each vertex and time point during the [-0.2 2.5 s] time window for each block and a clustering algorithm formed groups of vertices and time points based on these tests. The neighbourhood was defined based on a distance measure (maximum neighbour distance of 10). In order for a data point to become part of a cluster, they were thresholded at $p < 0.05$ (based on a two-tailed dependent t-test, using probability correction) and it had to have at least 10 neighbours. The sum of the t-statistics in a sensor group was then used as a cluster-level statistic (e.g., the `'maxsum'` option in Fieldtrip), which was then tested using a randomization test using 500 runs. In order to simplify the visualization of the source-space we only show the regions that were statistically significant or close to significant. Although the results section will report all these clusters (in order not to hide any information), based on Guthrie and Buchwald (1991) the discussion section will not take into account clusters which last less than 10 consecutive data points (i.e. 40 ms). This constraint is widely used in the EEG literature (Murray et al., 2001; Molholm et al., 2002; Kecskés-Kovács et al., 2013; Berger et al., 2014). For the blocks with no significant

	Control	Violation
Pre-test		
Spanish	0.95 (0.94, 0.96)	0.04 (0.02, 0.07)
Basque	0.28 (0.21, 0.35)	0.67 (0.55, 0.77)
Training		
1	0.95 (0.93, 0.97)	0.09 (0.05, 0.16)
2	0.97 (0.95, 0.98)	0.05 (0.02, 0.12)
3	0.99 (0.98, 1.00)	0.03 (0.01, 0.1)
Generalization		
Basque	0.99 (0.98, 0.99)	0.03 (0.01, 0.09)
Post-test		
Spanish	0.98 (0.97, 0.99)	0.05 (0.01, 0.14)

Table 3.4: Proportion (95% CI) of acceptable labels for the control and violation phrases of the comprehension task as a function of test phase. Proportions are taken from a mixed-effects model of the single-trial behavioral data.

cluster, the cluster with the lowest p-value is shown in order to show the trend of the data in that block.

3.3 Results

Behavioural analysis: Comprehension training and test

Table 3.4 shows proportion (95% CI) of acceptable labels for the control and violation phrases of the comprehension task as a function of test phase. In all conditions except the Basque pre-test, participants had good discrimination between the violation and control phrases. They could correctly label the grammatical stimuli as acceptable with a proportion greater than 0.95 and they could exclude the errors in most cases. In the pre-test for Basque, however, participants labeled the control stimuli acceptable less than half the time (0.28), and correspondingly mislabeled the violation stimuli more than half the time (0.67). As a consequence, participants' accuracy (i.e., the proportion correct in the violation and the control conditions) was lower than chance in the Basque pre-test (this response bias is discussed in section 3.4), but near ceiling in the other blocks.

	Singular	Plural
Training		
1	0.96 (0.94, 0.98)	0.97 (0.91, 0.99)
2	0.98 (0.97, 0.99)	0.98 (0.94, 1.00)
3	0.99 (0.98, 1.00)	0.99 (0.93, 1.00)
Generalization		
Basque	0.99 (0.98, 1.00)	0.99 (0.89, 0.99)
Post-test		
Spanish	1.00 (0.99, 1.00)	0.99 (0.92, 1.00)

Table 3.5: Proportion of (95% CI) produced correct phrases for the singular and plural conditions as a function of test phase. Proportions are taken from a mixed-effects model of the single-trial behavioral data.

Behavioural analysis: Production training and test

Table 3.5 shows proportion of (95% CI) correct phrases produced for the singular and plural conditions as a function of test phase. In all conditions, participants produced phrases that were labeled as grammatically correct or incorrect, according to the correctness only involving the use of the newly acquired rule and not other aspects of the production (such as pronunciation or the precision of the vocabulary). They could correctly produce the grammatical phrases for both singular and plural conditions at a level greater than 0.96 (see Table 3.5).

MEG data: Comprehension training and test

Time-locked analysis

Figure 3.3 illustrates a summary of the ERF analysis (average number of included trials per block are provided in Table 3.3). In the Spanish pretest (Figure 3.3b), the onset of the sentence does not differ between violation and control conditions. Only after the critical point do both conditions start diverging, where the violation phrases had a greater amplitude response than the control phrases and the difference lasted approximately one second. However, the statistical analysis supports the difference in a smaller time window. The analysis revealed a cluster only between 240 and 600 ms after the averaged critical point. This cluster includes bilateral temporal and posterior sensors (clusterstat=6686; $p < 0.002$).

Figure 3.3a shows that during the Basque pretest there were similar responses for both the violation and control phrases. The statistical analysis did not show any significant clusters (clusterstat<250; $p > 0.2$).

Regarding the training blocks, the ERFs in all three blocks the violation and control conditions do not differ before the average critical point occurs. After this point the violation phrases had a greater amplitude response than the control phrases and the difference lasted approximately 100 ms. Although in the time domain the three training blocks show similar patterns, in the spatial domain there is an evolution from block to block. In the first training block (see Figure 3.3c) the effect was spread through almost all the sensors but the largest difference was found on a group of right frontal sensors and also on some left posterior-temporal sensors between 29 ms and 126 ms after the mean critical point (clusterstat=966.5; $p=0.004$). In the second training block (see Figure 3.3d), the effect was less widespread and it mainly appeared in the left hemisphere between 0 ms and 142 ms after the mean critical point (clusterstat=1422; $p=0.002$). And finally, in the third training block (last block with feedback, see Figure 3.3f), the effect was localized on both left and right temporal sensors between 50 ms and 142 ms after the mean critical point (clusterstat=375.5; $p=0.048$).

The Basque generalization test (see Figure 3.3g) showed a response similar to the one found in the third training block: the magnitude of the effect was maintained and the topography involved sensors of both hemispheres' temporal areas. The statistical analysis revealed a significant cluster between 50 and 150 ms after the mean critical point (clusterstat=1220; $p=0.008$) formed by right temporal sensors.

Finally, the Spanish post-test (see Figure 3.3h) showed a different pattern from the Spanish pre-test. Both conditions started to diverge later than in the pre-test block and the magnitude of the difference was smaller than in the Spanish pretest. Moreover, although the topography was quite widespread, the main difference was located on right frontal sensors. The statistical analysis showed a significant cluster (clusterstat=1514; $p<0.002$) consistent with the effect we described, between 586-736 ms after the mean critical point, formed mainly by right frontal sensors.

Source level analysis

Time-constrained statistical analysis

Figure 3.4 summarizes the results of the time-constrained statistical analysis at the source level (i.e. after source reconstruction with MNE). Numbers below each block name indicate the time window used for the analysis (based on sensor level analysis). The first column shows the source localization of the cluster. The middle column shows whole brain raw differences between conditions (violation-control) for the given time window. And, the right column shows the statistical information of the given cluster. The labels of the regions come from the AAL atlas.

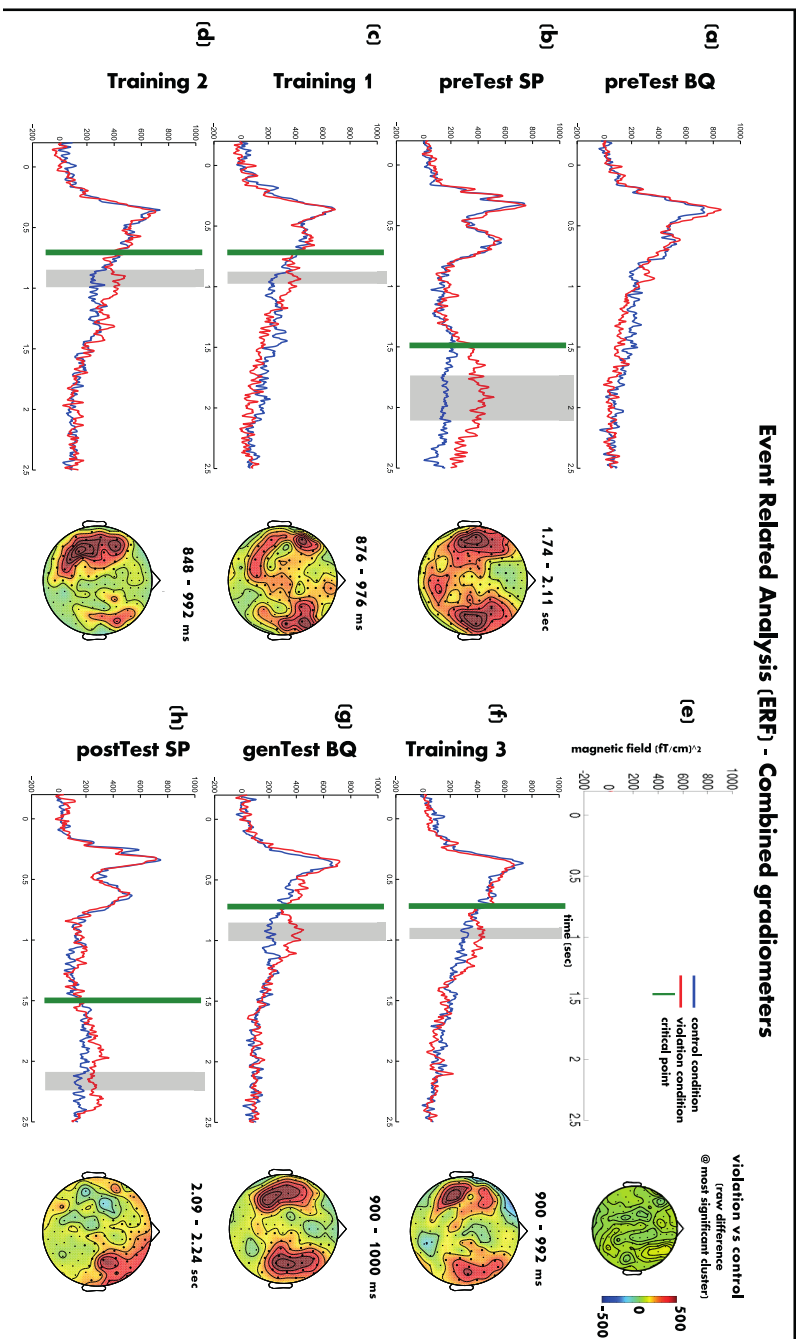


Figure 3.3: The plotted waveforms represent the averaged ERFs across all the sensors, the grey boxes show the time windows where the cluster was significant and the topography plots show the raw difference between the violation and control conditions in those time windows. In order to simplify the visualization this figure shows only the cluster with the lowest p-value for each block. Blue waveforms correspond to the control condition, red waveforms to the violation condition and the green vertical line denote the average critical point of each block. Blocks appear in the order they were run (a-h), with the scales given in (e).

In the Spanish pre-test (see first box in Figure 3.4), the statistical analysis showed a significant difference between violation and control responses coming from a cluster (clusterstat=6218; $p=0.004$) formed by a spread bilateral network. The network included right superior motor area, right frontal superior area and both left and right: parietal lobe (superior parietal, pre- and post-central gyri), frontal lobe (orbitalis, opercularis and triangularis), temporal lobe (Heschl's, middle and superior temporal gyri and middle and superior temporal pole), parieto-occipital areas (supramarginal and angular gyrus), fusiform and middle occipital lobe. This cluster is consistent with the spread topography found at the sensor level.

For the first training block in Basque (see second box in Figure 3.4), the statistical analysis showed a significant difference between violation and control responses coming from a cluster (clusterstat=2176; $p=0.004$) located mainly in the right hemisphere. The cluster includes right parietal lobe (superior motor area, pre- and post-central gyri), frontal lobe (middle and superior frontal gyri, triangularis opercularis), parieto-occipital areas (supramarginal and angular gyrus), temporal lobe (Heschl, inferior, middle and superior temporal gyri and middle and superior temporal pole), fusiform and left superior motor area. This pattern is also consistent with the sensor level topography which shows the effect mainly on right frontal and temporal sensors.

Regarding the second training block in Basque (see third box in Figure 3.4), the statistical analysis showed a significant difference between violation and control responses coming from a cluster (clusterstat=1430; $p=0.004$) located mainly in the left hemisphere. The cluster is formed by left parietal lobe (superior parietal area, pre- and post-central gyri), temporal lobe (inferior, middle and superior gyri), parieto-occipital areas (supramarginal and angular gyrus), superior occipital area and fusiform. This pattern is also highly consistent with the sensor level analysis.

In the third training block (see fourth box in Figure 3.4), the statistical analysis showed a near to significant difference between violation and control responses coming from a cluster (clusterstat=357, $p=0.051$) in the left hemisphere. This cluster is formed by left temporal lobe (inferior, middle and superior gyri), inferior occipital gyri and fusiform. In this case there is a small mis-match with the sensor level. The sensor level topography shows a bilateral effect on both hemispheres' temporal sensors, while the statistical analysis at the sensor level picks only the right hemisphere sensors, and the statistical analysis at source level picks up the left hemisphere regions.

The source level statistical analysis of the generalization test in Basque (see fifth box in Figure 3.4), does not show any significant cluster. Therefore, we show here

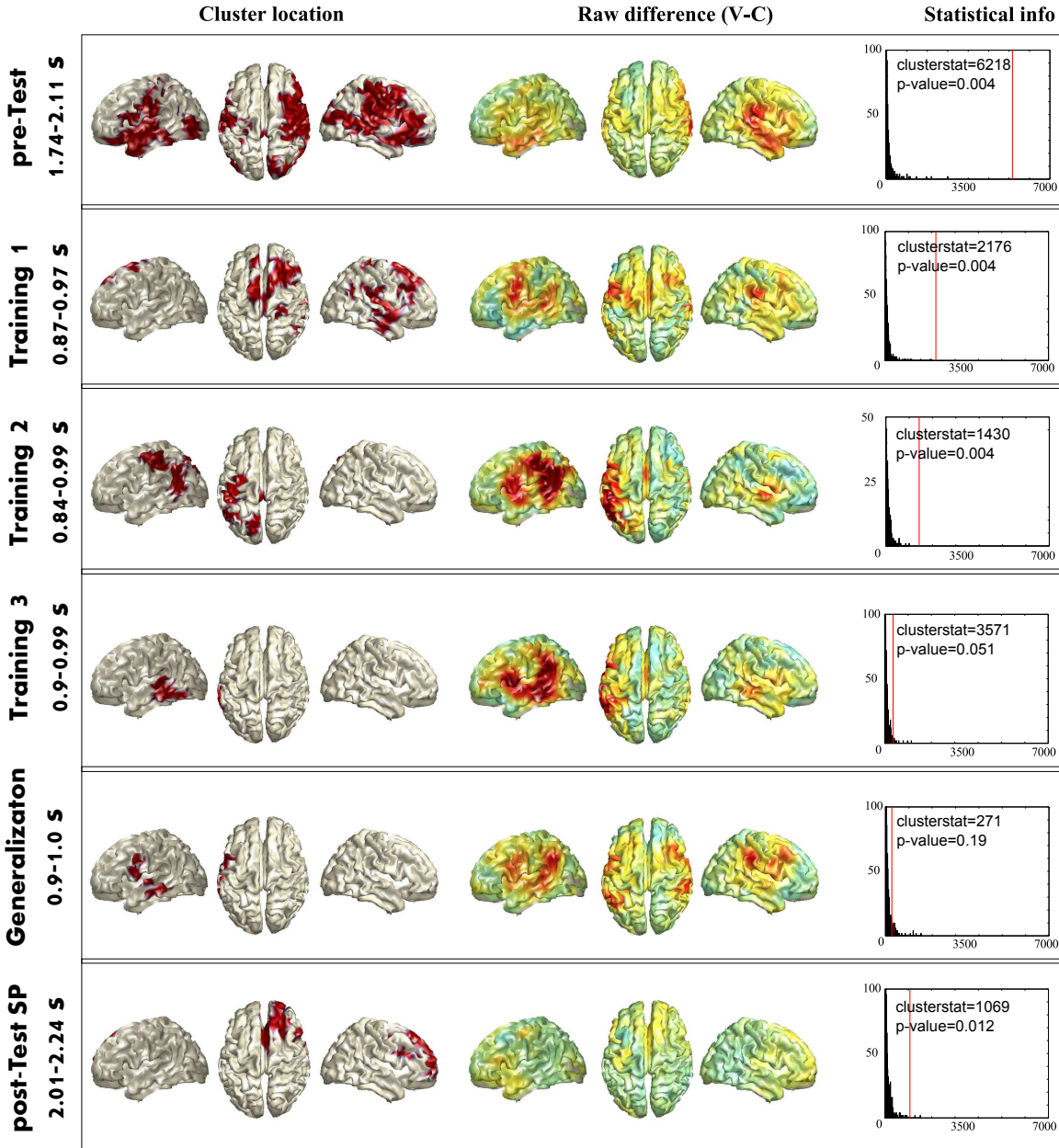


Figure 3.4: Summary of the time-restricted analysis. Each horizontal box shows the significant cluster of a block (when a block had no significant cluster the one with the lowest p-value is presented). The left column shows the source localization of the cluster. The middle column shows whole brain raw difference between conditions (violation-control) for the given time window. And the right column shows the statistical information of the given cluster: In blue the histogram of the random distribution, and the red line denotes the clusterstat value of that cluster.

the cluster that is closest to significance (clusterstat=271; $p=0.19$) in order to at least show the trend of this block. This cluster is formed by left parietal lobe (opercularis, pre- and post-central gyri) and temporal lobe (inferior, middle and superior gyri). This pattern is consistent with the sensor level topography, although this is not a significant result, and should be carefully interpreted.

Regarding the Spanish post-test (see sixth box in Figure 3.4), the statistical analysis revealed a significant cluster (clusterstat=1069; $p=0.012$) located mainly in the right hemisphere. It is formed by right parietal lobe (pre-central gyrus and superior motor area) frontal lobe (opercularis, triangularis, orbitalis, middle and superior-frontal gyri) and left superior motor area. This pattern is highly consistent with the sensor level analysis, although it differs from the pattern at Spanish pre-test.

Unconstrained statistical analysis

Figure 3.5 summarizes the results of the unrestricted statistical analysis using the same layout as Figure 3.4. However, this section does not compare the results with the sensor-level analysis.

In the Spanish pre-test (see first box in Figure 3.5), the statistical analysis showed two significant clusters. The first cluster (clusterstat=12614; $p=0.004$) appeared between 1.84 and 2.01 s and was localized at right parietal lobe (supramarginal, pre- and post-central gyri) and superior temporal gyrus. The second cluster (clusterstat=5619; $p=0.008$) appeared between 1.484 and 1.612 s and was localized at left parietal lobe (inferior parietal area and post-central gyrus).

For the first training block in Basque (see second box in Figure 3.5), the unrestricted analysis did not reveal any significant cluster. The cluster with the smallest p-value (clusterstat=1391; $p=0.47$) appeared between 924 and 940 ms and was localized at right inferior parietal lobe (supramarginal, pre- and post-central gyri) and superior temporal gyrus.

The second training block (see third box in Figure 3.5) gave two significant clusters. The first one (clusterstat=11044; $p=0.002$) was found between 844 and 944 ms and was formed by left parietal lobe (supramarginal, pre- and post-central gyri) and left angular gyrus. The second cluster (clusterstat=3383; $p=0.016$) was found between 1.044 and 1.08 s and located at left inferior parietal area, supramarginal and angular gyri.

In the third training block (see fourth box Figure 3.5) there was no significant cluster. The cluster with the lowest p-value (clusterstat=1410; $p=0.14$) appeared

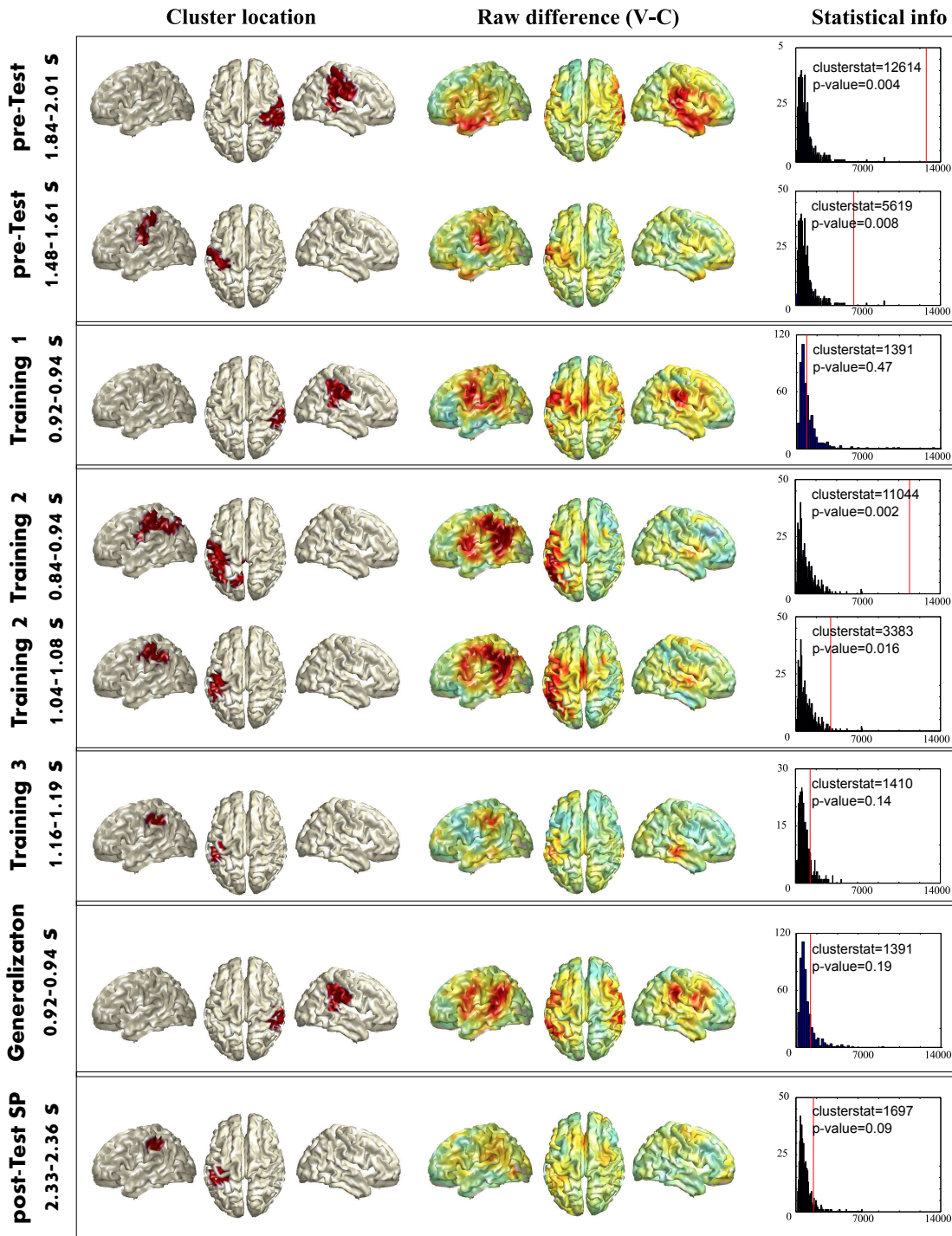


Figure 3.5: Summary of the unrestricted analysis. Each horizontal box shows the significant cluster of a block (when a block had no significant cluster the one with the lowest p-value is presented). The left column shows the source localization of the cluster. The middle column shows whole brain raw difference between conditions (violation-control) for the given time window. And the right column shows the statistical information of the given cluster: In blue the histogram of the random distribution, and the red line denotes the clusterstat value of that cluster.

between 1.16 and 1.19 s and was located at left parietal lobe (supramarginal, pre- and post-central gyri).

The generalization block (see fifth box in Figure 3.5) did not show a significant cluster either. The cluster with the lowest p-value (clusterstat=1391; $p=0.19$) was found between 924 and 940 ms and located at right parietal lobe (inferior parietal area, supramarginal, and post-central gyri) and superior temporal gyrus.

Finally, the Spanish post-test (see sixth box in Figure 3.5) gave a marginally significant cluster (clusterstat=1697; $p=0.09$) between 2.33 and 2.36 s and located at left parietal lobe (inferior parietal area, supramarginal and post-central gyri).

Summary of both source level analyses

In general, the unrestricted statistical analysis has less statistical power than the restricted analysis. Moreover, when the clusters from both analyses are compared directly, although some patterns could be considered similar, most of the clusters do not overlap in location. The reader might assume that the analyses are describing different observations and that we should find a measure that lets us decide in favor of one or the other. However, when the clusters obtained in each type of analysis are compared with the raw difference between violation and control conditions and/or the sensor level data, all the clusters are consistent with a given part of the raw difference. Therefore, it may be that each analysis is sensitive to a different part of the violation-control effect, providing complementary results that help to better understand the neural processes behind the task.

3.4 Discussion

The present study investigated ERFs and their source localization related to morphosyntactic number agreement during the training sessions and a generalization test in adult learners of a simple grammar fragment. In general, the results showed that ERFs can change quickly during second language acquisition, and that the violation-related responses related to the discrimination of correct and incorrect Basque phrases can emerge within hours of training. The sources of these violation-related responses appear to be localized in areas broadly similar to native language responses, when considered at a whole-brain scale of analysis. Below, the results from each block are discussed separately before providing a general discussion.

Pre-Test Basque

Participants' accuracy on the pre-test block was below chance, suggesting that participants were either choosing randomly with some bias, or systematically misclassifying the stimuli. While it is counterintuitive that accuracy was below chance, participants appeared to classify the stimuli according to the surface morphology rather than an underlying rule. Although this is speculative, it may be that in this type of task, Spanish speakers are more likely to classify a phrase as grammatical Basque to the extent that the phrase includes Basque-specific inflectional morphology (e.g., '-a' or '-ak') not found in Spanish. Nonetheless, the absence of differences in the ERF waveforms between the violation and control conditions suggests that there was no cue in the stimuli (e.g., prosodic or phonological differences) that would differentiate the conditions.

Pre-Test Spanish

As expected, the accuracy in this block was at ceiling, confirming that participants were paying attention to the task and following the instructions. We found that the ERFs followed a similar time course and sensor-topography in both the violation and the control conditions, with a greater response magnitude in the violation condition. No statistical differences between the violation and control conditions were present until 240 ms after the critical point, and then the violation response was stronger compared to the control condition for around one second. The difference was mainly found on bilateral temporal sensors, although it was present also in some parietal and occipital sensors. Consistent with the sensor-level analysis, the source-level analysis showed that the effect was localized mainly at the bilateral parietal and temporal lobes.

Training

Learners achieved high performance beginning in the first training block, and there were corresponding ERF differences between the violation and control trials. The onset of the effect relative to the critical point was a little earlier than the Spanish pre-test timing, and the duration of the effect was shorter (150 ms versus 360 ms in Spanish) in all three training blocks. Also, the spatial localization of these effects differed from block to block.

Based on the behavioral results, it might be assumed that if performance is high from the first training block, learning has already occurred and that the subsequent training blocks were not reflecting learning. However, this assumes that having

knowledge is the same as applying knowledge in real time as sentences or phrases unfold. However, it has been already proposed that learners need time before they transfer the rule-based knowledge into their real-time language processing system (McLaughlin et al., 2010).

In the first training block the effect was mainly located on right parietal sensors and on a few left temporal and posterior temporal sensors. Both source analyses showed that the effect is mainly located at right fronto-parietal lobes and temporal lobe. Regarding the second training block, the effect was mainly found on left hemisphere sensors and some of the right frontal sensors. Source analyses showed a pattern consistent with the sensor-level analysis. At the source level the violation condition elicited a strong response in the left parietal and the temporal lobes, and a slightly more reduced response in the occipital lobe. As for the third training block, similar to the second training block, the effect was mainly located at bilateral temporal sensors. The topography of this block resembles the topography of the Spanish pre-test block. Both source level analyses trend to locate the effect in left temporal lobe, inferior-occipital gyri and fusiform. However, these results were marginally significant and the interpretation should be cautious. In this case there is a small mismatch with the results for the sensor level analysis. The sensor level topography reveals a bilateral effect on both hemisphere temporal sensors. While the statistical analysis at the sensor level only shows the right hemisphere sensors, the statistical analysis at source level reveals the involvement of the left hemisphere regions.

The first training block effect was localized in right frontal areas. This area has been previously related with non-syntactic specific error detection processes (Indefrey et al., 2001). Moreover, based on the HERA model (Habib et al., 2003), right prefrontal cortex is involved in memory retrieval while left prefrontal cortex is involved in memory encoding. The fact that right frontal areas seem to be the main sources of the effects found in this block suggests that on this first training block some memory retrieval process is involved in the judgment of grammaticality in early phases of grammar learning.

The second training block showed a left-lateralized effect although right frontal sensors show also some difference between the violation and control conditions. The third training block's sensor level topography showed that the effect is found at bilateral temporal areas, similar to the pattern we found in the Spanish pre-test. When moving to source-level analysis, similar to the second training block, the effect is mainly present in language-related areas but the pattern still differs from the Spanish pre-test (recall that the Spanish pre-test showed the effect on the both left and right hemispheres). From previous fMRI studies it is known that the localized areas have been found to be part of the language network involved in

speech comprehension (Friederici, 2011). Similarly, Davidson and Indefrey (2009b) studied the MEG response to phrase-order violations in German learners of Dutch, and a source reconstruction of that activity implicated a variety of left-hemisphere perisylvian areas showing a greater amplitude response to grammatical violations months after formal coursework. The fact that the main effect occurs in language areas could suggest that the new L2 memories are being created and embedded in regions that already process lexical and grammatical information, rather than in separate regions that are responsible for other cognitive processes.

Nevertheless, even if these are language-related areas, the effects found in these blocks still differ from effects found in Spanish (remember that the Spanish pre-test showed the effect on both hemispheres) and their statistical support is only marginally significant. A possible explanation that could account for this effect is that in these blocks participants are relying on a more automatized process than in the first training block. Nonetheless, the response still differs from the one that is involved in their L1, and it could be that this difference in proficiency is reflected in the amplitude of the evoked response.

Finally, one can probably not exclude intrinsic variability of the MEG signal as an explanation for the block-to-block differences seen during training. While it was the case that the behavioral discrimination was at a high level for the participants, the magnitude of the violation effect was smaller and shorter in duration. Because smaller differences are associated with greater statistical variability, some of the block-to-block differences may be associated with the variability of the effect.

Generalization test

The performance level found on the three training blocks was maintained in the generalization test. The stimuli that were used in this test were formed by novel nouns and adjectives that had not been presented during the training and the task did not provide any feedback to the participants. Therefore, it appears that participants were able to generalize the rule learned on the training blocks to novel phrases.

Regarding the neural correlates of this block, the ERF analysis showed an effect onset consistent with the previous blocks. The effect magnitude was comparable to that found for the second and third training block and Spanish pre-test, and the topography showed that the effect was mainly localized at bilateral temporal sensors similar to the third training block and the Spanish pre-test. However, the source level analyses did not give any significant result. The trend indicates that areas responsible of the effect could be some of the areas found in the Spanish pre-test: left parietal

lobe (opercularis, pre- and post-central gyri) and temporal lobe (inferior, middle and superior gyri) and right inferior parietal area, supramarginal, and post-central gyri. However, a strong conclusion can not be drawn due to lack of statistical power.

In this block two of the measures (behavioral and sensor level) show similar patterns compared the Spanish pre-test, suggesting that responses to morphosyntactic manipulations early in training can be shaped towards the L1, and generalized to novel words. Although it is not statistically significant, both source level analyses show a trend also towards an L1-like pattern. Nonetheless, the timing of the effect in Basque occurs relatively early compared to the Spanish effect. This kind of paradigm has not been much studied in Basque and, therefore, it is hard to compare the timing of the effect with previous literature. It may be the case that violation responses in Basque and Spanish do not coincide in time. We doubt that the effect in Basque could appear due to stimuli-differences because the Basque pre-test shows no violation-control effect. Moreover, the timing of the effect is consistent across all of the training blocks and the generalization test. This gives us confidence that the effect found is a violation-control effect. However, further study is needed to disentangle if the source-level absence of results is due to statistical power or because the effect is not really maintained in the generalization test.

Post-test Spanish

The behavioural results showed that participants performed well on the post-test obtaining similar scores compared to the Spanish pre-test, as expected.

Surprisingly, the ERF analysis showed differences between the Spanish pre-test and post-test. The post-test effect started considerably later (580 ms after critical points instead of 240 ms) and lasted only 150 ms (the pre-test effect lasted around 360 ms). Moreover, the effect magnitude was reduced and the topography was different. The post-test effect was mainly localized on right frontal sensors and some left frontal sensors. The time-restricted source level analysis showed that right frontal areas are involved in the violation-control effect, however the non restricted analysis showed a trend towards left parietal areas and a different timing.

There are different possible explanations for this discrepancy between Spanish pre- and post-test. The Spanish post-test was one of the last blocks of the session and participants could have been fatigued. Even if they gave the correct response, the route used for getting the response could be different. Another more plausible explanation is that the discrepancy could be a result of a switch effect. In the second session, participants went through a training block and the generalization test in

Basque. Hence, subjects were immersed in the Basque tasks for around one hour, and they then needed to perform the same task in their recently-inhibited L1. However, this study was designed to focus on the learning process of a grammar rule and not on this particular issue, so we are not in a position to confidently opt for one or the other explanation. In future studies, a second Spanish block should be run after a break to have a more conclusive result.

General discussion

Based on both the behavioural results and the electrophysiological responses, we found that when a grammar rule is taught individually in an intensive training paradigm, learning can occur rapidly (within hours). Moreover, it is accompanied by changes in neural responses that are similar to L1-like patterns, as has been shown in previous studies (Davidson and Indefrey, 2009a,b, 2011; Mueller et al., 2005, 2007, 2008). Nevertheless, these results differ from other studies, finding that adult learner' brain responses differed from the ones of native speakers (Pakulak and Neville, 2011; Meulman et al., 2014; Díaz et al., 2016). We hypothesize that the source of these different results could come from the fact that training studies, because they measure responses earlier in the learning process, may capture different dynamics than longer-term studies. Nevertheless, some other studies that also compared native speakers and adults learners did show native-like patterns in adult learners (Kotz et al., 2008). Moreover, Morgan-short et al. (2010) suggested that the differences and similarities between natives and learners are not only dependent on the maturity of the learners, but on the interaction of several different factors such as age, proficiency, and training type (see also Caffarra et al., 2015). Another interpretation that has been given to these differences is that they could reflect a transitional stage where participants have not reached the proficiency that would lead to an L1-like electrophysiological response (Osterhout et al., 2006). Tanner et al. (2013) have suggested that the differences found at the individual level reflect the stage of L2 acquisition.

The present study was designed to study the brain dynamics during learning at early stages, rather than mid- to long-term learning and consolidation. Given this constraint, our design does not allow us to reach a strong conclusion about whether learners of Basque would achieve Spanish-like responses in the long term. However, we think that it is important to work in this direction to have a better understanding of why and when discrepancies and similarities between native speakers and adult learners arise. For example, Meulman et al. (2014) showed that learners of Dutch did not show native-like brain responses to gender violations. Díaz et al. (2016) suggest that differences like these are related to language distance. They tested Spanish native

speakers who had learned Basque early or late in life, using sentences that could contain a syntactic violation on subject-verb agreement (present in both L1 and L2), object-verb agreement (agreement exists in L1, but this specific agreement is only present in L2) or ergative agreement (unique to L2). They found that regardless of age of acquisition (AoA), participants did not show native-like brain responses to the rule only present in L2.

Nonetheless, even though we looked only at 'single rule learning', in our view, the main finding in the present study is the localization of grammar learning. It has been suggested that different subsystems of language rely on different cortical areas that may show different degrees of plasticity (Sanders et al., 2008). Syntax and phonology are known to be the subsystems which present more difficulties when learned in adulthood. While several studies investigated the source localization of tasks related to phonology learning (for a review see Zhang and Wang, 2007), the literature provides few studies for source reconstruction of tasks that reflect early stages of grammar learning (Davidson and Indefrey, 2009b; Hultén et al., 2014).

Although ultimate attainment is still debated, recent studies have focused on comparison of native speakers versus non-native speakers who were familiar with the language for a long time prior to the study (Meulman et al., 2015; Hanna et al., 2016; Sung et al., 2016; Díaz et al., 2016; Johnson et al., 2016). However, few of them used a technique that allowed for source localization (Hanna et al., 2016). The present study shows that it is possible to characterize brain dynamics during grammar learning, and compare the L1 and L2 response within participants.

When looking at the training blocks, a commonality among the last two blocks is found: evoked activity for the control and violation conditions was found in the left hemisphere, more exactly in left temporal (inferior, middle and superior gyri) and parietal (supramarginal, pre- and post-central gyri) lobes and left angular gyrus, although this was not the case for the first training block (see below). There are not many MEG studies that focus on early grammar learning on adult learners. Davidson and Indefrey (2009b) studied the MEG response to phrase-order violations in German learners of Dutch, and a source reconstruction of that activity implicated a variety of left-hemisphere perisylvian (inferior frontal and left temporal lobe) areas showing a greater amplitude response to grammatical violations months following formal coursework. In addition, Hultén et al. (2014) trained Finnish native speakers to produce short phrases in a miniature artificial language requiring morphosyntactic object agreement. After four days of training participants were tested with a MEG production task. Agreement modulated the evoked response strength in left superior temporal and right occipito-temporal cortex. Despite the commonalities

just described, we were able also to see some dynamics during the training, in the sense that different areas were more predominantly active in different blocks.

Regarding the patterns of evoked activity found on the first training block, they clearly differ from the patterns found in the other Basque blocks. Furthermore, the later blocks resemble the patterns found in Spanish (L1). More precisely, the source reconstructions show that in the first training block evoked activity is found in the left perisylvian network in both the control and violation conditions. However, in the following Basque blocks increased activity in the left perisylvian network is only found in the violation conditions. Although this is the general pattern found in the evoked activity, the statistical analysis does not support the whole pattern, but only some of the areas. As mentioned in the introduction, this work is an exploratory study. As initial stages of L2 learning remain under-studied, we are not in a position to make strong assumptions about the areas involved and restrict our analysis to those. Ideally, the patterns found in this study would help other studies to have a more constrained hypothesis and to perform a more classical confirmatory analysis.

In Davidson and Indefrey (2009b), the localization of the effect in the left perisylvian varied depending on the session of the recording (two weeks or three months of formal coursework in Dutch), where the responses of the early sessions localized the effect at left superior temporal areas, similar our results. Moreover, the first training block violation condition also shows increased evoked activity on the right supramarginal gyrus compared to the control condition, but the evoked activity in these region is not modulated by condition in the other blocks. According to Indefrey (2006) review of the literature about L2 processing in fMRI studies, task effort may be a factor. For example, the differences found in the early Basque blocks and Spanish block could reflect the degree of effort involved in the task, and the similarities found between L1 and L2 after the intensive training could reflect that participants learned to perform the task more effectively. Indefrey (2006) described differences between L1 and L2 BOLD signals during syntactic processing, especially when a metalinguistic judgment is required during the task. Studies focusing on morpheme inflection showed stronger activation of the dorsal left posterior IFG after training (2 months) compared to before training for L2 morpheme processing, and the area overlaps with the L1 processing area. When the same study was conducted on L2 learners with longer training (6 years) the BOLD signal in this area was much weaker. Indefrey (2006) suggests that when an area is involved in a linguistic task, at the beginning greater neural activity of this area could reflect the degree of effort put into the task, while after years of training the weaker activity could reflect that the task is being processed more effectively. Similarly, Zhang and Wang (2007) reviewed several phonetic and tone learning studies, showing that after some training, improvements

in performance were associated with increased BOLD signal in some areas from the left language network. However, after long-term learning, advanced learners showed a decreased BOLD signal after training. They suggested that these patterns show that cortical representations can change continuously with learning.

Therefore, the change of evoked activity found at source level from the first training block to the following blocks might be reflecting the progressive changes described in Indefrey (2006) and Zhang and Wang (2007). However, again, one cannot exclude intrinsic variability as an explanation for the block-to-block differences seen during training (see section 3.4). The goal of this study was to give an initial description of this variation, so that following studies can investigate whether the patterns are robust across different grammar rules and language combinations.

Finally, the materials of this experiment consisted of a fragment of grammar, and as described by Mueller et al. (2007), high level performance in this given task cannot be taken as proof of native-like proficiency in the 'complete L2'. It remains to be seen whether individual rule learning is reflected in similar activity when the rule is learned as part of a larger set of rules, or other aspects of the language.

3.5 Summary

The behavioral results show that, at least for small fragments of language and simple grammar rules, L2 adult learners can reach a high level of proficiency. Nonetheless, this is a miniature language, and the high level performance in this given task cannot be taken as proof of native-like proficiency in L2. More work should be done to understand how L2 learners process 'complete' syntactic information. Furthermore, the results show that electrophysiological responses during L2 processing that are similar to L1 responses can be seen after some hours of training (despite not being completely equal). In summary, changes in L2 processing can be found in short periods of time and, therefore, models of L2 learning should account for these rapid changes.

Chapter 4

Sentence processing experiment

4.1 Rationale

This chapter examines the role of cortical oscillations in language learning by comparing the response to a newly-learned versus an already-known language. As opposed to reading, relatively little is known about the oscillatory activity while listening an L2 language. Oscillatory changes due to language learning were tested using a comparatively long stimulus, allowing us to visualise changes in oscillatory activity in the theta (4-8 Hz), alpha (8-13 Hz) and beta (13-30 Hz) frequency bands. This work presents a source reconstruction analysis of induced activity recorded using magnetoencephalography (MEG) both before and after a few hours of Spanish training in adult native English speakers with no substantial knowledge of Spanish.

4.2 Material and Methods

Ethics Statement

The study was carried out at the Sir Peter Mansfield Imaging Centre and was approved by University of Nottingham Medical School Ethics Committee. All participants provided informed consent according to the Declaration of Helsinki before starting the experiment.

Participants

Eighteen (6 female, 12 male) healthy native speakers of English aged 21 to 57 participated in the experiment. Participants were recruited from within the Sir Peter Mansfield Imaging Centre, University of Nottingham, and were right-handed English native speakers with no knowledge of Spanish and reported no hearing or

reading disorders. All participants were screened for magnetic interference prior to data collection. Additional data from two subjects was recorded, but the data were discarded from the analysis, one due to excessive magnetic artifacts and the other due to a failure to meet the behavioural requirements of the training.

Stimuli

Following Hochmuth et al. (2012), matrix sentences composed of a relatively small number of words but that allow a large number of sentences to be constructed, were employed. Each sentence was made up with a subject (i.e., a given name) and four other words: a verb, a numeral, an object, and an adjective. Each category was composed of 5 words, and therefore we were able to construct 625 unique semantically correct sentences for each condition in English and Spanish ($5 \times 5 \times 5 \times 5 = 625$). By using the concept of matrix sentences, words become unpredictable but at the same time comprehensible. This means that in order to understand the entire sentence each word must be understood: it is not possible for participants to memorise whole sentences during the training session.

An additional set of English matrix sentences was defined from another set of vocabulary, different from the ones just explained. The two sets were constructed to control for translation effects - this is explained in more detail in the design section.

Stimuli were recorded in a sound-proof booth using a native female voice for each language. The resulting audio amplitude was equalized to the same loudness and presented via Promold ear inserts (International Aquatics Trades, Santa Cruz, CA) and EARTONE 3A Insert Earphone transducers (EAR Auditory Systems) at a comfortable listening level of approximately 55 dB.

Design and task

The study was carried out in two experimental sessions on two consecutive days. The main reasons to opt for a two-day design was to enable the consolidation of the knowledge acquired in the training stage, and due to the need of a substantial number of trials so that the participants achieved a high level of comprehension. Figure 4.1 summarizes the design. The first session (Figure 4.1, panel A left column) included 5 blocks: an initial resting state, followed by a period of sentence listening in English, a period of sentence listening in Spanish, a comprehension test in Spanish, and a session of training in Spanish. The second session (Figure 4.1, panel A right column) included 4 blocks: an initial resting state, followed by a period of sentence listening in

English, a period of sentence listening in Spanish and comprehension test in Spanish. Each of the blocks is explained below.

Resting State (MEG): Resting state data were acquired during 10 minutes during which the subjects were instructed to remain still while fixating their eyes on a white cross on a grey background.

Sentence Listening (MEG): Stimulus sentences were presented in groups of four (10 sec.) preceded by 10 sec. of silence. Each block consisted of 30 trials (120 sentences) and lasted approximately 10 minutes in total. For each session, one block was performed in English and one in Spanish. The stimuli in English in the first day, and both recordings in Spanish included matrix sentences from the first vocabulary set whereas stimuli in English in the second day included matrix sentences from the second vocabulary set. The reason for using a different set of vocabulary for English on the second day, is to avoid any intent of translation from English to Spanish, ensuring pure English listening. To avoid the higher cost of switching from non-native to native language (Costa and Santesteban, 2004), the English block always preceded Spanish.

Comprehension test in Spanish (Behavioural): In this task, participants completed a translation of 25 auditory Spanish matrix sentences into written English. They only could hear each sentence once before writing down the answer.

Spanish Training (Behavioural): Training occurred after the MEG scan and behavioural test on Day 1. The training session lasted 1.5 - 2 hours. The structure of the training was based on previous work by Hultén et al. (2014) and was designed to initially build vocabulary, followed by comprehension of full sentences. The training block was divided in two phases Vocabulary learning and Sentence Comprehension (see Figure 4.1, panel B):

1) Vocabulary learning: Five pairs of English-Spanish words (e.g. 'Big - Grandes') were presented auditorily. After that, the same Spanish words were presented auditorily one at a time and the participant had to verbally translate each one back into English. Feedback was provided whether the translation was correct, and if it was incorrect the correct translation was provided. These two steps were repeated with the same pairs of words four times. This procedure was repeated until all the Spanish-English pairs were presented (see Figure 4.1, panel B).

2) Sentence comprehension training: The same training structure was used to train sentence comprehension. Five sentences were presented as English - Spanish pairs, then each Spanish sentence was presented and the participant had to verbally

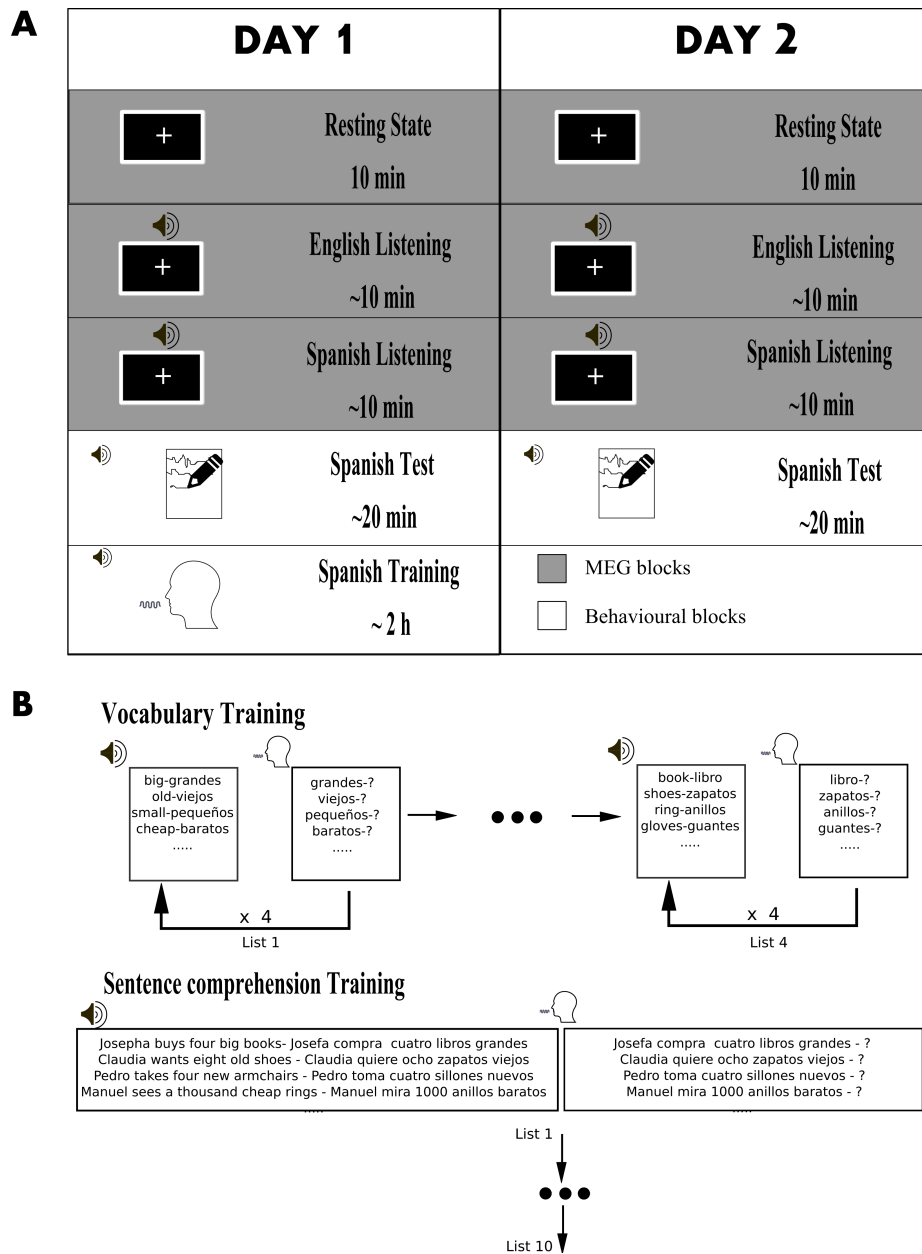


Figure 4.1: Design of the study. Panel A enumerates the tasks that were performed. The left column contains the tasks of the first session, and the right column shows the tasks of the second session. Dark grey blocks are blocks with MEG recordings. Light grey blocks are behavioural tasks. Panel B describes the training session in more detail.

translate this into English, with feedback, until they could consistently provide a correct answer. Participants were presented with eight blocks of those five sentences (see Figure 4.1, panel B).

Data Collection

All the blocks described in the design section were recorded for each participant. During the recordings, participants were asked to relax and acquire a comfortable position between blocks in order to prevent movements during data acquisition; they were instructed to avoid head, body and eye movements during the task.

MEG data were acquired in supine position at a sampling frequency of 600 Hz using a 275 channel CTF MEG system (MISL, Coquitlam, Canada) operating in third order synthetic gradiometer configuration. Three localisation coils were attached to the head as fiducial markers (nasion, left preauricular and right preauricular) prior to the recording.

A Polhemus Isotrak (Polhemus, Colchester, VM, USA) was used to digitize the head shape (around 400 points for each subject) and the fiducials in order to be able to coregister brain anatomy to the MEG sensor array. Volumetric anatomical MR images were also acquired using a 3T MR system (Phillips Achieva, Best, Netherlands) running an MPRAGE sequence (1 mm³ resolution). Following data acquisition, the head surface was extracted from the anatomical MR image and coregistered (via surface matching) to the digitised head shape for each subject. This allowed complete coregistration of the MEG sensor array geometry to the brain anatomy, thus facilitating subsequent forward and inverse calculations.

Analysis

Behavioural analysis

In order to score the behavioural test, for each correctly translated word (except the name) one point was scored. As mentioned in the Participants section, one participant was excluded because his score was lower than 50%.

MEG data

Using DataEditor software from CTF MEG (MISL; Coquitlam, BC, Canada), the recorded MEG data were band-pass filtered between 1 - 150 Hz and demeaned. Line frequency (50 Hz) and its harmonics were filtered with a notch filter. Then, data

were visually inspected for artefacts. Any trials containing excessive artifacts or head movement above 5 mm were removed. In particular, trials containing characteristic signatures of the magneto-myogram, magneto-oculogram or magneto-cardiogram signal were excluded. Based on this evaluation, one participant was excluded from the analysis due to excessive magnetic artifact. Table 4.1 summarizes the average number of trials included in the analysis of each block.

	Day 1	Day 2
English	26.22 (2.46)	27.33 (3.25)
Spanish	26.61 (2.72)	27.5 (3.07)

Table 4.1: Mean (std) number of trials per condition included in the MEG analysis.

Source level analysis

Following pre-processing, a beamformer spatial filtering approach was employed (Van Veen et al., 1997). In order to do that, a data covariance matrix within a 1- to 150-Hz frequency window and a time window spanning the whole experiment was calculated. Regularization was applied using the Tikhonov method with a regularization parameter equal to 5% of the maximum eigenvalue of the unregularized matrix. Voxels were defined at vertices of a regular (4 mm) grid spanning the whole brain volume and a forward model was constructed based on a dipole approximation and a multiple local sphere head model (Huang et al., 1999). The weights of the beamformer for the broad band (1-150 Hz) signal at each voxel were derived. After that sensor-level data was filtered into three bands: theta (4-8 Hz), alpha (8-13 Hz) and beta (13-30 Hz). Each band data covariance matrix was calculated using a time window spanning the whole experiment. Each frequency band covariance matrix was filtered using the broad band (1-150 Hz) weights in order to obtain power source-level maps of each frequency band. These source-level maps represent the relative power change between active and control windows: $(P_a - P_c)/P_c$. For each frequency band, whole-brain All>Null and Null>All contrasts were computed across all subjects and thresholded for statistical significance with $q < 0.05$ (FDR corrected) in order to identify the main power dynamics of each band.

Two different statistical analyses were performed: A whole brain analysis and a ROI analysis. The first one allows us to make inferences from the results. For the ROI analysis a contrast was defined to identify (for each frequency band) the regions that show statistically significant differences compared to baseline. Subsequently,

differences across conditions in these regions were examined. Since the regions were selected based on statistical significance in the whole-brain analysis, the tests performed in the ROIs are biased to show significant results. Nonetheless, this analysis can be very useful for exploring patterns of activity across conditions in order to set priors for future studies (Poldrack, 2000).

Whole brain analysis

For each frequency band, whole-brain 2 (Language: English vs. Spanish) by 2 (Session: Day1 vs. Day2) ANOVAs were performed and thresholded for statistical significance with $q < 0.01$ (FDR corrected). Post-hoc analyses (paired t-test) for significant factors were performed in the main clusters surviving the whole-brain threshold.

ROI analysis

The whole-brain All>Null and Null>All contrasts ($q < 0.05$, FDR corrected) were used to define the regions of interest for each frequency band. For each region the mean power in each particular band was extracted for further hypothesis-driven analyses based on 2 (Language: English vs. Spanish) by 2 (Session: Day1 vs. Day2) ANOVAs, with all the factors varying within subjects.

4.3 Results

Behavioural analysis

Table 4.2 shows the percentage (standard deviation) of correctly translated words of the comprehension test as a function of day. Participants' accuracy on the first day was low, whereas accuracy on the second day increased substantially.

	Day 1	Day 2
Spanish	7.94 (6.6728)	81.46 (10.85)

Table 4.2: Mean (std) percentage of correctly translated words.

MEG data

Source level analysis

Whole brain analysis

Whole brain contrast

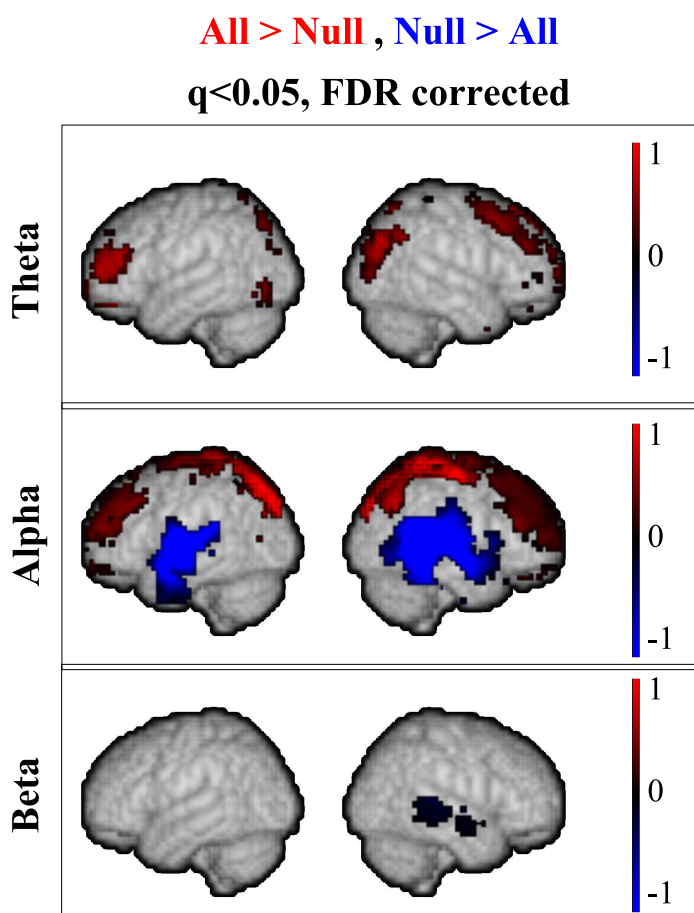


Figure 4.2: Brain regions showing statistically significant All>Null (red) and Null>All contrasts (blue) ($q < 0.05$, FDR-corrected).

Figure 4.2 shows the power-differences found with the whole brain All>Null and Null>All contrasts ($q < 0.05$, FDR corrected) for each frequency band. The whole-brain contrast All>Null yielded power-differences in bilateral occipital, bilateral frontal and right parietal regions for theta band and dorsal regions for alpha band. The opposite contrast Null>All yielded power-differences in left and right temporal and inferior-parietal regions for alpha band and right middle temporal lobe for beta band.

The whole-brain ANOVAs ($q < 0.01$, FDR corrected) yielded statistically significant clusters only for the Language factor. Brain activity differences due to language were found in the left pre-frontal cortex for the theta and alpha bands, and in bilateral temporal lobes for the alpha and beta bands (see Figure 4.3, panel A). No significant clusters were found for the main factor Session, or the interaction of Language and

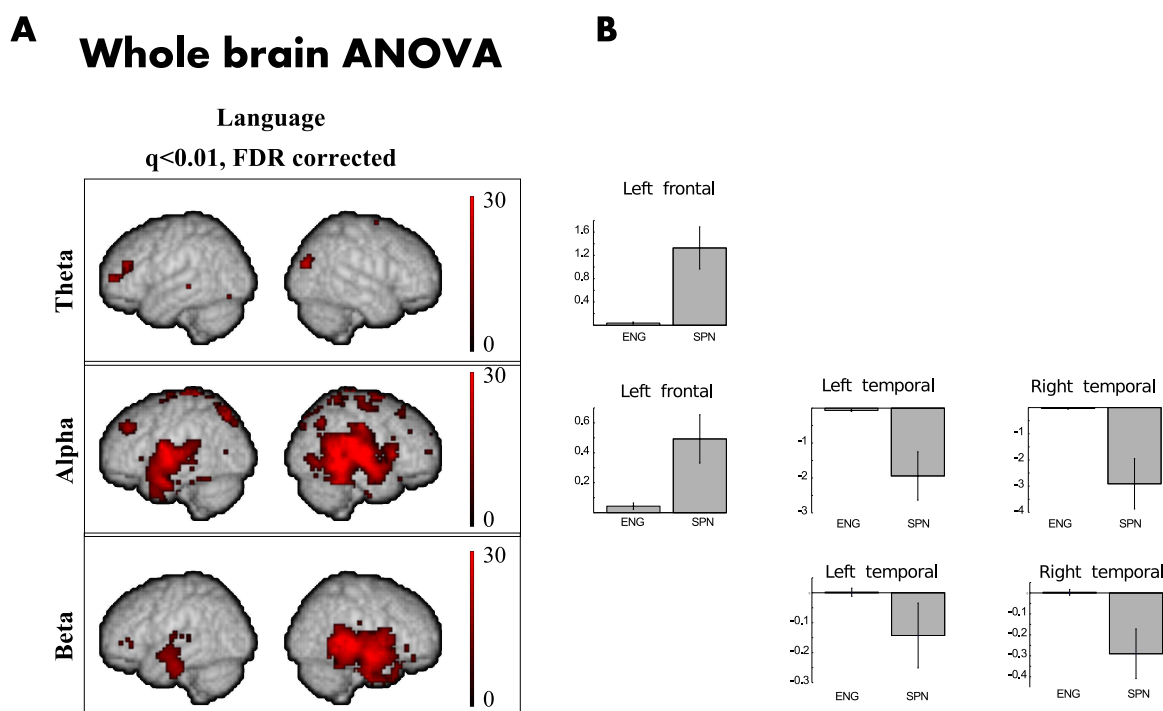


Figure 4.3: Results from the whole-brain 2 x 2 ANOVA. Panel A presents F maps of the Language factor ($q < 0.01$, FDR-corrected). Panel B presents the post-hoc analysis of the main clusters from panel A.

Session.

A post-hoc analysis (see Figure 4.3, panel B) revealed a larger theta and alpha power increase for Spanish compared to English listening in the left prefrontal cortex ($t = -3.67$; $p < 0.001$ for theta and $t = -3.01$; $p < 0.001$ for alpha). The alpha power decrease was larger for Spanish compared to English listening in both left and right temporal lobes ($t > 2.78$; $p < 0.001$). The beta power decrease was significantly larger for Spanish compared to English in the right temporal lobe ($t = 2.66$; $p = 0.008$). A trend ($t = 1.45$; $p = 0.08$) was also found in the left hemisphere.

ROI analysis

Figure 4.4 shows the summary of the ANOVA analysis done in the regions of interest for each frequency band. As a general finding, all regions and bands showed a major effect of Language ($F > 8.86$; $p < 0.004$).

Regarding theta band power, both occipital and fronto-parietal regions showed stronger theta synchronization in Spanish blocks compared to English blocks ($F = 8.86$; $p = 0.004$ for occipital and $F = 11.13$; $p = 0.0014$ for fronto-parietal regions). Moreover, bilateral frontal and right parietal regions also showed a major effect of Session

($F=6.62$; $p=0.0123$) and an interaction between Language and Session ($F=6.72$; $p=0.0113$).

Regarding alpha band power, in the dorsal regions alpha synchronization was higher in response to Spanish blocks compared to English blocks ($F=9.4$; $p=0.0031$). On the other hand, there was greater alpha desynchronization in response to Spanish blocks in bilateral temporal and left inferior-parietal regions ($F=11.52$; $p=0.0012$ for left hemisphere and $F=13.94$; $p=0.0004$ for right hemisphere). A post-hoc analysis revealed a trend ($t=-1.36$; $p=0.09$) that shows that alpha power decrease in left temporal and inferior-parietal regions for the Spanish second session is lower than for the first session (and closer to English patterns), but no effect was found for the right temporal region ($t=0.2463$; $p=0.37$).

Regarding beta band power, desynchronization was larger in the Spanish block than in the English blocks ($F=11.18$; $p=0.014$).

4.4 Discussion

The aim of this study was to examine the effects of short-term language learning on cortical oscillatory activity in native English speakers. Source reconstruction techniques were used to quantify the spatial response in three frequency bands: theta (4-8 Hz), alpha (8-13 Hz) and beta (13-30 Hz). A whole brain analysis determined the power during the active window relative to a control window for each frequency band, and provided us with the general pattern of power across frequency bands during speech comprehension.

The whole brain analysis revealed that theta and alpha power increased relative to baseline in frontal and occipital areas, whereas alpha power decreased in the right temporal lobe and left temporal and inferior-parietal lobes. Beta band power decreased in the right temporal lobe. The power increases and decreases across frequency bands are consistent with studies in the literature, although the literature shows no consensus on the topography of these power modulations (see Bastiaansen and Hagoort, 2006, for a review).

In the two analyses, alpha and beta decreases in right temporal lobe showed similar modulation patterns and localization, suggesting that these decreases in both bands are a broad band effect (Lam et al., 2016).

Theta band

In the theta band a power increase with respect to baseline in bilateral frontal, right parietal and bilateral occipital areas was observed. The whole-brain ANOVA

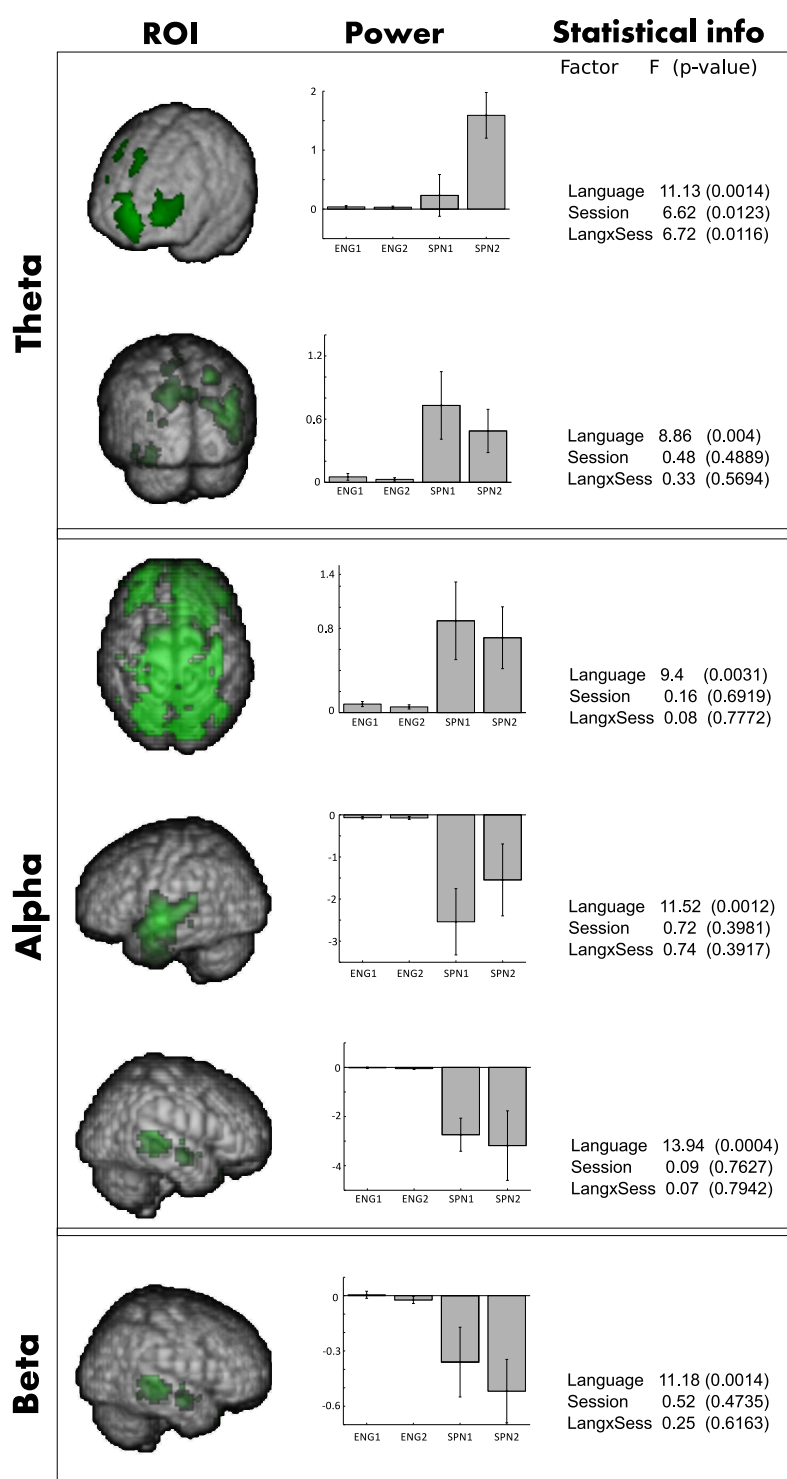


Figure 4.4: Exploratory ROI analysis results. The first column denotes the frequency band, the second the ROI analyzed (binary mask in green), the third column shows power at that given ROI for the four conditions and the last column shows the results of the ANOVA.

analysis showed that the Spanish condition had a stronger theta synchronization than the English condition in the left frontal cortex. Previous studies on language comprehension related theta synchronization with lexical retrieval (Lam et al., 2016; Bastiaansen et al., 2008, 2005). On this basis, the observed theta synchronization modulations might reflect lexical retrieval differences during sentence comprehension depending on the language. Regarding the modulations found at bilateral frontal and right parietal regions, the spatial topography of those effects is similar to the topography found by Lam et al. (2016). In this study, words late in the sentence were found to elicit stronger theta synchronization in these areas compared to words early in the sentence. This pattern recalls the frontal-parietal network that is associated with cognitive task demands: The authors suggest that words late in the sentence are likely to increase task demands since a more extended representation must be maintained in memory. Nonetheless, in contrast to these studies, in the present work apart from retrieving words from memory, participants had to segment speech (i.e., concurrent word recognition and speech segmentation). It may be the case that speech segmentation and word recognition are related. Previous studies have shown lexico-semantic information is used to help listeners to perform a segmentation task when the task is performed in a native language (Sanders and Neville, 2000). Moreover, these lexical cues are also available in non-native speakers (Sanders et al., 2002). Related to this, recent work suggests neural correlates of different linguistic structures in speech: syllables, phrases and sentences (Ding et al., 2015).

The exploratory ROI analyses suggested that the occipital areas might show a similar pattern: a larger theta increase for Spanish listening compared to English. Moreover, a possible interaction between language and session was found in the bilateral frontal areas. The second session in Spanish elicited stronger theta synchronization than first session while there was no difference between the English blocks. However, these results may be biased due to the selection of the ROIs and therefore theta modulations due to language learning should be studied in more detail in further studies.

Alpha and beta band

Regarding the whole brain analysis, in the alpha band we found a power decrease with respect to baseline in bilateral temporal lobes and a power increase in the dorsal part of fronto-parietal and occipital lobes. Reductions in the amplitude of alpha oscillations are assumed to reflect states of high excitability of the underlying pyramidal cell populations, while increases in alpha power would reflect periods of low excitability: a state of inhibition (Klimesch et al., 2007). Others have attributed coding capacity to these changes ((Hanslmayr et al., 2012)): During higher excitability

stages, pyramidal cells fire less synchronously which increases entropy (a measure of information richness), thus increasing the coded information. On the contrary, during lower excitability stages the entropy is smaller and the coded information is more redundant (Hanslmayr et al., 2012). In line with this, it has been shown that together with alpha desynchronization (ERD) in task-related regions, alpha synchronization (ERS) is found in task non-related regions (see Klimesch et al., 2007, for a review). Moreover, Zumer et al. (2014) studied the role of alpha in information gating and found that in a visual attention task alpha ERD was found in the contralateral hemisphere and alpha ERS in the ipsilateral hemisphere of the attended object. Consequently, the desynchronization in the alpha and beta bands observed in our data could reflect a state of information processing, whereas alpha synchronization in dorsal areas could reflect a state of inhibition.

On this basis, the alpha power decreases and increases found here seem to suggest that the bilateral temporal lobe and part of the inferior-parietal lobe are recruited during speech processing, which is consistent with previous speech processing models (e.g. Friederici, 2011). Furthermore, the post-hoc analyses showed that the Spanish listening condition elicits stronger power increases and decreases than English. Following previous assumptions, this would indicate that areas of the language network show a stronger neural desynchronization, thus, more information processing for Spanish (non-native) than for English (native), whereas areas out of the network show stronger inhibition for Spanish (non-native) than for English (native). One possible explanation is that the areas with alpha power desynchronization reflect the effort of semantic and syntactic unification. Although beta and gamma power increases have been traditionally related to unification processes (Bastiaansen and Hagoort, 2006), recent evidence has related alpha and beta desynchronization with the unification of the syntactic and semantic information of the ongoing word (Lam et al., 2016). Furthermore, when a stronger context is provided, a facilitatory effect could explain that some regions are less involved in unification processes (Lam et al., 2016).

On this basis, the ROI exploratory analysis gives limited evidence bearing on learning related changes in brain regions and frequency bands that previously have been associated with unification processes. Alpha desynchronization in the left temporal lobe shows a small difference between the two Spanish sessions that is not strongly supported by statistics. Further studies need to further evaluate this hypothesis.

On the other hand, according to Bastiaansen and Hagoort (2006) when passive language comprehension is ongoing and participants have no task, alpha desynchronization reflects attentional processing and behavioural consequences,

but is not (necessarily) related to comprehension per se (see also Davidson and Indefrey, 2007). In our case no task was required while listening. Hence, the stronger alpha desynchronization could mean that participants were more engaged in Spanish listening than in English listening. This would also explain the large differences we found in modulation of different power bands between the two languages. At this point it is hard to determine if the differences found are due to pure speech comprehension differences or due to different attentional demands. Further work needs to be done to differentiate this. In the present work, no task was used during listening since this could shift the different processes of speech comprehension to more posterior areas in native speakers (Friederici, 2011). However, there is no literature about how this kind of shift occurs in non-native speakers. If a task had been used to ensure participants were paying attention to the stimuli, it would be difficult to determine if differences are due to pure speech comprehension or differences in the shift of the processes. Therefore, we opted for a more naturalistic passive listening task.

Finally, one can not directly exclude the confound of block order. Although all the results have been discussed from a language effect point of view, it can not be ignored that English always preceded Spanish blocks, in order to avoid a switch cost effect (Costa and Santesteban, 2004). It is easier to switch from the dominant language to the second language than from the second language to the dominant language. Therefore, if the design was counterbalanced, English blocks performed after Spanish blocks would suffer from the switch cost and would not be a reliable native-listening control. If the results were influenced by block order, oscillatory effects of fatigue or stimulus repetition should be found. Previous studies have shown that repetition of stimuli decreases oscillatory power of the gamma band (Grill-Spector et al., 2006). On the other hand, fatigue is associated with alpha increases at occipital areas (Von Bünau et al., 2010; Berger, 1929). Therefore, the pattern of modulations found in this study suggests that the oscillatory modulations are not due to block order, but due to a language effect.

Regarding language learning effects, no strong evidence was found for oscillatory modulations due to language learning. This could be because the frequency power analyzed in this work reflects the response to the entire sentence which includes many cognitive functions that occur during sentence listening (e.g., Friederici, 2011). Moreover, participants underwent a very specific and focused short training which may lead to more subtle changes compared to a full long-term classroom training. It could be the case that focusing on a short time interval may be more sensitive to the changes that occur due to one language training session.

4.5 Summary

This work investigated the spatial dynamics of neural oscillations during sentence listening in native and non-native speech. The responses to non-native language listening prior to training and after one training session were compared, as well as to the native language listening response. Our results showed that theta band power was synchronized in bilateral frontal and right parietal areas, which have been associated with task demands. The power modulations found in this band suggest that lexical retrieval is more demanding in non-native speech listening. Regarding the effects in alpha and beta bands, there is a clear difference between the response to native and non-native language. However, these language effects should be interpreted cautiously since one cannot exclude the block order confound. Finally, no strong evidence has been found for learning effects, suggesting that oscillatory measures seem less sensitive for measuring short-term language learning related changes that are integrated over a sentence.

Chapter 5

Memory in L1 experiment: A view on alpha and tau rhythms

5.1 Rationale

The experiment of Chapter 4 showed that oscillatory changes in response to sentence listening due to learning are hard to detect. This may occur because many cognitive functions take place in the course of a sentence (Friederici, 2011; Hagoort, 2016). It may be the case that when focusing on short time interval measures, oscillatory changes are easier to identify. The experiment of this chapter steps back in order to better understand the oscillatory mechanisms of memory retrieval in L1.

Apart from studying how memory retrieval occurs in adults, studying which simple methods could improve memory is also of great interest. For example, behaviourally it has been shown that eye-closure benefits memory retrieval of eye-witnesses, at least in their L1 (Vredeveldt, 2011; Vredeveldt et al., 2012).

Nevertheless, to the best of our knowledge, no attempt has been made in order to understand the neural mechanism underlying the memory boost of eye-closure. Apart from its behavioural benefits (Vredeveldt, 2011; Vredeveldt et al., 2012), it is well known from the electrophysiological literature that eye-closure increases alpha power (Berger, 1929). Moreover, alpha power modulations have been related to memory retrieval performance: participants who remember more items in the retrieval phase show larger alpha desynchronisation during the retrieval phase than participants who perform poorer (Klimesch, 1999). Furthermore, performance has been increased in other cognitive tasks when alpha power has been modulated externally (Klimesch et al., 2003; Hanslmayr et al., 2005). However, how eye-closure alpha power increases modulate physiological mechanisms of memory retrieval remains unstudied.

The study described in this chapter is an episodic memory task in L1, where the retrieval phase of the task is performed auditorily. This allows us to perform the retrieval phase with both eyes closed and open and therefore study simultaneously: 1) how auditory alpha rhythm is modulated in the retrieval phase of an episodic memory task, and 2) how eye-closure (visual alpha modulation) interacts with the auditory alpha rhythm and affects task performance.

5.2 Alpha oscillations and memory

Alpha is a rhythm in the range of 7 to 13 Hz and it has the highest amplitude among all the rhythms; indeed, it is one of the few rhythms that can be seen with the naked eye in the M/EEG signal. However, alpha is not the only rhythm that fluctuates in this frequency range. Previous studies have identified two other 7-13 Hz rhythms apart from alpha: the mu rhythm and a third rhythm (later termed tau). The mu rhythm is an oscillation that is present in motor-related areas, and is associated with desynchronization when participants perform motor tasks (Pfurtscheller et al., 1997). Similarly, the third or tau rhythm is found in middle temporal region and seems to be independent from posterior alpha and mu rhythms (Hari, 1993). This tau rhythm also seems to desynchronize when participants listen to auditory stimuli (Hari et al., 1997). Klimesch (1999) suggests that the tau rhythm is difficult to capture with EEG recordings but is easier to detect with MEG or intracranial recordings. This may be the reason why well-known alpha-effects in different memory tasks that used visual stimuli have not been found when using auditory stimuli. For instance, Krause used a vowel recognition memory task to study auditory memory (Krause et al., 1996). Despite alpha desynchronization being found in response to the stimuli in the retrieval phase, alpha desynchronization modulations due to performance were not found. In a previous study, they found that when tones (instead of vowels) are used to study auditory memory, not even the classical alpha desynchronization is found (Krause et al., 1995). The aim of the present experiment is to take advantage of the MEG ability to capture the tau rhythm to study whether if in episodic memory auditory stimuli modulates tau rhythm as alpha rhythm is modulated with visual stimuli. Moreover, the experiment will allow us to investigate how visual alpha interacts with the tau-rhythm.

Alpha (and beta) desynchronization is found in response to stimuli both during encoding and retrieval phases for short-term (e.g. Klimesch et al., 1993), semantic (e.g. Doppelmayr et al., 2005) and episodic (e.g. Klimesch et al., 1997) memory-tasks. Moreover, the amount of alpha desynchronization has been related to performance of the task. Klimesch (1999) suggested that a large decrease in alpha/beta

band reflects good cognitive and memory performance. Regarding the encoding phase, larger alpha desynchronization has been found for later remembered words compared to later forgotten words (known as the subsequent-memory effect) (Klimesch et al., 1997; Hanslmayr et al., 2012). Regarding the retrieval phase, larger alpha desynchronization has been found for good performers (i.e. the ones who remembered more words) compared to bad performers (i.e. those who remembered fewer words, Klimesch et al., 1993). Larger alpha desynchronization related to better performance has not only been found in different memory tasks (short-term, semantic and episodic) (for a review see Klimesch, 1999; Hanslmayr et al., 2012, 2016) but also in other cognitive tasks such as mental rotation (Klimesch et al., 2003; Hanslmayr et al., 2005).

Moreover, the magnitude of alpha desynchronization in response to a stimulus depends on the absolute power of alpha in the pre-stimulus interval. The larger the absolute alpha power in the pre-stimulus interval, the larger the alpha desynchronization in response to the stimulus. As mentioned in the previous paragraph, larger alpha ERD have been related to better performance in a variety of tasks. Taking advantage of these two facts, Klimesch et al. (2003) modulated alpha power dynamics in a mental rotation task. They increased absolute alpha power during the baseline period using TMS; this induced greater alpha desynchronization in response to the stimuli, which resulted in better behavioural performance. Similarly, Hanslmayr et al. (2005) used Neuro Feedback Training to increase absolute alpha power in the baseline period. Results are similar to the ones found by Klimesch et al. (2003): higher absolute alpha power during the baseline period induced larger alpha desynchronization in response to the stimuli, which resulted in better performance for the task.

Despite the large volume of research on alpha's role in memory, and the numerous demonstrations that eye closure boosts posterior alpha, the influence of eye closure on the alpha oscillation's role in memory retrieval remains unstudied. Nevertheless, the role of eye-closure on memory retrieval has been studied in several behavioural studies (Glenberg et al., 1998; Wagstaff et al., 2004; Perfect et al., 2008, 2011; Vredeveldt, 2011; Vredeveldt et al., 2011, 2012). These studies report several cases in which eye closure and disengagement from the environment increased the number of recalled items or experiences.

There are two main psychological hypotheses to explain the beneficial effect of eye closure on memory. The first is the cognitive load hypothesis, which suggests that memory improvement comes from freeing cognitive resources by closing the eyes (Perfect et al., 2008, 2011). The second, is the modality specific interference hypothesis, which suggests that reducing visual interference by closing eyes promotes

visualization of the event and improves memory (Vredeveldt et al., 2011, 2012). Nonetheless, the link between alpha's role in memory, alpha power increase due to eye closure and the influence of eye closure on memory performance remains understudied.

5.3 Materials and Methods

Ethics Statement

The study was carried out at the Basque Center for Cognition, Brain, and Language, and it was approved by its institutional review board.

Participants

Participants were twenty-one (11 male, 10 female) neurologically healthy, native Basque-speaking, right-handed adults with no hearing or reading disorders. All participants were screened for magnetic interference prior to data collection, and provided informed consent (Declaration of Helsinki) before starting the experiment. Additional data from two subjects was recorded: data from one subject were discarded because the participant fell asleep, and data from another subject did not provide behavioural responses.

Design and Materials

Memory performance of participants was assessed using a recognition task containing nine blocks. Each block consisted of three parts: encoding (50 trials), rehearsal (5 min) and retrieval (50 trials) for a total duration of 11 minutes. During the encoding part, visual words were presented on a back-projection screen, and participants read the words to be memorized. In the rehearsal phase they were asked to think silently about the words they just read. For the retrieval part, participants listened to probe words and they had to recognize words that had been present in the encoding phase by pressing a green button for yes and a red button for no. Each participant performed the task in two conditions. Half of the blocks instructed the participant to perform both the rehearsal and the retrieval phase of the task with eyes closed (EC) and the other half of the blocks with eyes open (EO; see Figure 5.1). The order of the EC and EO conditions of the blocks was counterbalanced across participants.

Participants performed the task in Basque, and the words in each list were randomly selected from a bigger set of words with similar frequency ($\log_{10}(\text{freq})$),

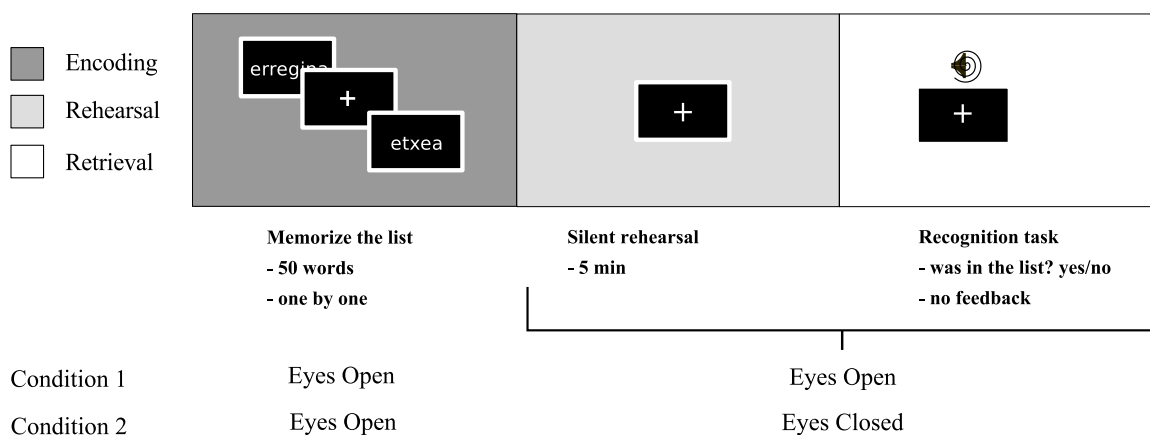


Figure 5.1: Design of the experiment. The first phase (encoding) of the experiment was done always with eyes open, with visual stimuli. Second (rehearsal) and third (retrieval) phases were performed in two conditions: Eyes closed and eyes open, with auditory stimuli.

mean=1.02; std=0.69) length (mean=7; std=2.06) and syllable number (mean=4; std=0.95). All the words were nouns that referred to concrete and imageable concepts of every-day life.

For the encoding phase of the task participants were asked to read the words silently and memorize the list of fifty words. Words were presented one by one, on a black screen. The duration of each word on the screen was two seconds.

The rehearsal part was five minutes long and participants were asked to rehearse the words they read during encoding. Before the experiment participants were instructed that during rehearsal as soon as they noticed that they were distracted to start thinking on them as soon as possible.

In the retrieval phase, participants listened to fifty words (25 to be remembered, 25 to be rejected). They had five seconds from the onset to reject or accept the word. If in that time they did not respond to that word, the next word was played. If they responded to it, they had to wait the remaining time (from the five seconds) to listen to the next word. If more than one answer was given, only the first one was used.

Procedure

The data were recorded using a 306-channel Elekta Neuromag (Elekta Oy, Helsinki, Finland) located at the MEG laboratory of the Basque Center on Cognition Brain and Language in Donostia. The MEG is located in a magnetically shielded room (passive shielding; Vacuumschmelz GmbH, Hanau, Germany).

Participants were told to relax and acquire a comfortable position between blocks in order to prevent movements during data acquisition; they were instructed to avoid head, body and eye movements during the task. Two (vertical and horizontal) EOG channels and a single bipolar ECG lead were recorded for heartbeat and eyeblink removal by ICA. Afterwards, two blocks of two minute length resting state with eyes closed and eyes open were recorded.

A Polhemus Isotrak (Polhemus, Colchester, VM, USA) was used to record points on the head for alignment of the head coordinates to each subjects structural MRI (MPRAGE, 1 mm³ voxel size). Additionally, four head localization coils were attached to the participants head, and their spatial location (relative to fiducials) was recorded. The four coils were active during the MEG recording to provide continuous head position information (cHPI). MEG data was acquired with a 1000 Hz sampling rate and high-pass filtered at 0.03 Hz and low-pass filtered at 330 Hz during acquisition.

Data Analysis

The purpose of the first block was habituation to the task and the MEG. Therefore, it was discarded from the data analysis and only the remaining the eight blocks were used for data analysis.

Behavioural Analysis

The proportion of trials with successful recall was modeled with a generalized linear mixed effects regression model with the Laplace approximation as well as posterior simulation (Dixon, 2008), using the factor eye closure (open, closed). Two models were compared, the first one with participants random effects for the intercept ($m2=Hit \sim Eyes + (1 + Eyes|Sbj)$) and the second one including participants random effect for the eye closure factor ($m2=Hit \sim Eyes + (1 + Eyes|Sbj)$).

In order to establish if there were behavioural differences between eyes closed and eyes open a region of practical interest (Kruschke, 2011, ROPE,)) of one-item difference in memory recall was defined. In other words, that eye closure would be considered to have an effect on behaviour only if performance from both conditions (eyes closed and eyes open) statistically differs by at least one item.

MEG data

Using MaxFilter 2.2, the recorded MEG data were filtered using temporal Source Space Separation (tSSS) with a four second time window and a minimum

correlation of 0.98. Each individual's head origins and bad channels were supplied manually. Data were downsampled to 250 Hz, and line frequency (50 Hz) and its harmonics were filtered. Following recommendations from the MEG laboratory at MRC Cognition and Brain Sciences Unit (http://imaging.mrc-cbu.cam.ac.uk/meg/Maxfilter_V2.2), the downsampling and the filtering were conducted in two separated steps. The data were processed using Fieldtrip toolbox version 20141202 (Oostenveld et al., 2011).

First, data from the retrieval period were segmented into epochs. The onset of the epoch was locked to the onset of the word. Data were segmented into five second epochs consisting of two seconds before the onset of the trial and three seconds following the onset of the trial.

The data were then screened for jump and other noise artifacts, padded to 12 seconds per trial and then filtered with a low-pass FIR filter at 40 Hz (one pass-zero phase), and the resulting epochs were baselined and detrended with respect to the whole interval. For further eye and heartbeat artifact reduction, the data were decomposed using the fastICA algorithm where the number of components was set equal to the number of sensors (204 gradiometers). No data dimension reduction algorithm was applied prior to ICA. Then, the correlation of each ICA component time-course with the HEOG, VEOG, and ECG time-course was calculated. The components whose correlation exceeded three standard deviations of the mean correlation in any of the cases (HEOG, VEOG, or ECG) were removed before back projecting the single-trial data into the original sensor space.

Eye-closure effect

First, alpha power modulations due to eye closure, both during the resting state and retrieval phase were compared. For that, the first 30 seconds of the resting state with eyes closed, and with eyes opened were used. In addition, the first 30 seconds of the retrieval part for the first block with eyes closed and first block with eyes opened were extracted for each participant. Power values were calculated using a single Hanning taper based on frequency-dependent window length. There were six cycles per time window, which was sliced in steps of 1 sec. The analysis was performed in the whole epoch (30 sec) and between 0 and 40 Hz in steps of 1 Hz. This resulted in linearly-variant frequency smoothing of 1.7 Hz at 10 Hz. Absolute power values were used for this analysis. After that, gradiometers were combined and the statistical analyses were performed on the combined gradiometers.

A statistical analysis of alpha was conducted to test the eye-closure effect. A randomization distribution of cluster statistics (Maris and Oostenveld, 2007) was

constructed over sensors (power was averaged over frequency and time) and used to evaluate whether there were statistically significant differences between conditions in the alpha band (7 - 13 Hz). In particular, t-statistics were computed for each sensor and a clustering algorithm formed groups of channels over time points based on these tests. The neighbourhood definition was based on the template for combined gradiometers of the Neuromag-306 provided by the Fieldtrip toolbox. The threshold for a data point to become part of a cluster was set at $p=0.05$ (based on a two sided dependent t-test, using probability correction), with at least two neighbours. The sum of the t-statistics in a sensor group was then used as a cluster-level statistic (e.g., the maxsum option in Fieldtrip), which is then tested using a randomization test using 1000 runs.

Time-frequency analysis

After this comparison, the dynamics of the retrieval phase were studied. Oscillatory power of the retrieval phase was examined using a single Hanning taper based on frequency dependent window length (six cycles per time window) which was sliced in steps of 0.05 s. The analysis was performed in the whole trial (between -2 and 3 s) and between 0 and 40 Hz in steps of 1 Hz. This resulted in linearly-variant frequency smoothing of 1.7 Hz at 10 Hz. Power values for each time-frequency point were normalized relative to the baseline period (-0.5,0) s. Afterwards, gradiometers were combined and statistical analyses were performed on the combined gradiometers.

Restricted statistical analysis

An a priori alpha band analysis was performed to test the hypothesis outlined in the introduction: alpha ERD in the retrieval phase is larger for remembered items compared to forgotten items. Moreover, eye closure should elicit larger alpha ERD compared to the eyes open condition. For the statistical analysis, a randomization distribution of cluster statistics (Maris and Oostenveld, 2007) was performed in the alpha band (7 - 13 Hz) during the (-0.5, 2) s time window. The rest of the parameters remain the same as in the previous statistical analyses.

Unrestricted statistical analysis

Finally, an unrestricted frequency analysis was performed to complement the previous analysis and check for any effect in other frequency bands not contemplated in the hypothesis. A randomization distribution of cluster statistics (Maris and Oostenveld, 2007) was performed on all the frequencies during the (-0.5, 2) time

window. The rest of the parameters remain the same as in the previous statistical analyses.

Source level analysis

Dynamic Imaging of Coherent Sources (DICS) (Gross et al., 2001) was used for source reconstruction of the data. Structural MRI were segmented into scalp, skull brain and CSF, and a volume conduction model was constructed based on this segmentation using a single shell approximation (Nolte, 2003) by assigning conductivity to the brain. This volume conduction model and a 8 mm grid (available in Fieldtrip) were used to construct the leadfields. Cross-spectral density matrices were calculated around 10 Hz (with a smoothing window of 3 Hz) for three time windows of interest (0.5 1), (1. 1.5) and (1.5 2) s. For each time window of interest complex spatial filters (common for the four conditions) were constructed using the leadfields and the cross-spectral density matrices of the window and the baseline (-0.5 0). Afterwards, data were filtered using the common filters and the power changes relative to baseline were calculated for each condition.

For the statistical analysis, a randomization distribution of cluster statistics (Maris and Oostenveld, 2007) was performed in each of the time windows (0.5 1), (1. 1.5) and (1.5 2) s. The rest of the parameters remain the same as in the previous statistical analyses.

5.4 Results

Behavioural Analysis

As Table 5.1 shows, the model indicates that performance of the participants is around 0.75 and does not differ across conditions. When the two models were compared, no benefit of including the participant random effect of eye-closure ($\Pr(>Chisq)=0.96$) was found. Therefore, only the first model is reported.

	m1
Eyes Closed	0.75 (0.70, 0.79)
Eyes Opened	0.76 (0.67, 0.82)

Table 5.1: Proportion (95% CI) of trials with successful recognition. The estimates of the first model and its confidence interval are shown ($m1=Hit \sim Eyes + (1 + 1|Sbj)$)

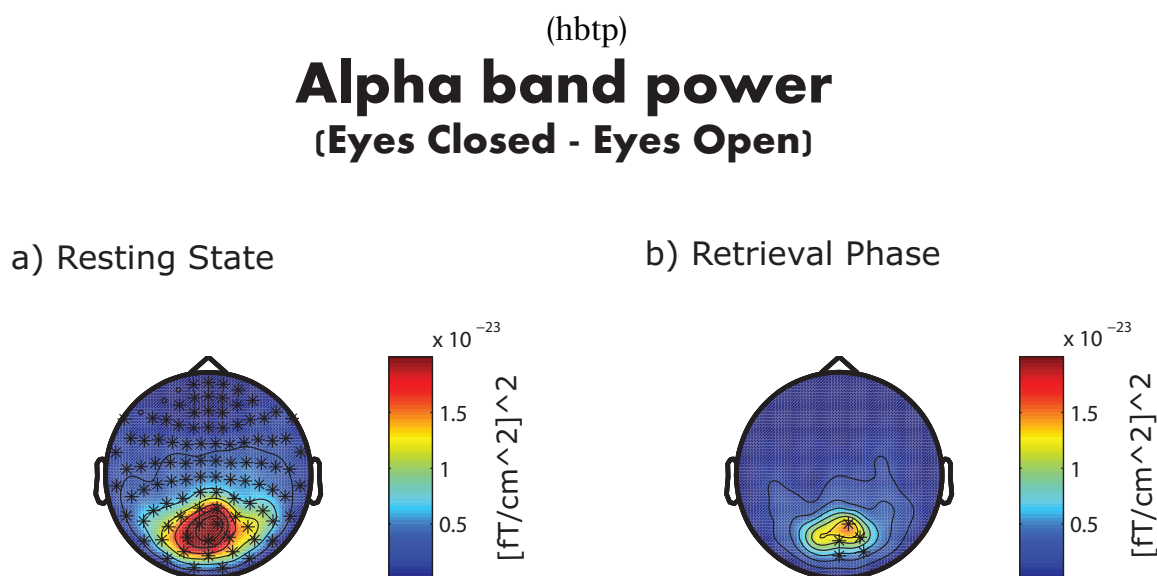


Figure 5.2: Alpha band (7 - 13 Hz) absolute power difference topographic distribution between eyes closed and eyes open, for resting state (a) and retrieval phase (b). Warmer colors denote greater power for eyes closed, and cooler colors denote small or almost no difference. Asterisks mark the sensors that were part of the cluster resulting from the statistical analysis.

MEG data

Eye-closure effect

Figure 5.2 displays the power difference in the alpha band (7 - 13 Hz) between eyes closed and eyes open for both resting state (a) and retrieval phase (b). Although both images indicate an alpha increase in similar posterior sensors with very similar topographies, the alpha power difference in the retrieval phase is smaller (see color bars). The statistical analysis for each EC-EO comparison revealed a positive cluster (clusterstat=343.5; $p < 0.001$) for the resting state comparison and another positive cluster near to the significance threshold (clusterstat=11.91; $p = 0.073$) for the retrieval phase.

Time-frequency analysis

Restricted statistical analysis

Figure 5.3 illustrates the results of the oscillatory power analysis as average time-frequency plots. The grand average (Figure 5.3i) shows the expected response to a spoken word stimulus: theta ERS between 0 and 0.5 s, and alpha ERD between 0.5 and 1 s, followed by a high-alpha/beta rebound between 1 and 2 s. This was found

in all conditions (eyes closed and eyes open) and items (remembered and forgotten). The differences described below are a modulation of this pattern. As described below, the comparisons reveal an ERD effect related to type of item (remembered vs. forgotten), but an ERS effect for eye closure (eyes closed vs. eyes open).

Comparing the different conditions, the data are consistent with the expected memory effect insofar that the remembered items were associated with a greater alpha ERD compared to forgotten items, for both eyes closed and eyes open conditions. For the eyes closed condition, the a priori statistical analysis in the alpha band (7-13 Hz) revealed a cluster (clusterstat=-2214; $p=0.002$) that lasted between 0.6 and 1.75 sec (Figure 5.3g). For the eyes open condition, there was a cluster (clusterstat=-1470; $p=0.006$) between 0.65 and 1.65 sec (Figure 5.3h).

Moreover, an eye closure effect was also found. For both type of items (remembered and forgotten) the eyes closed condition elicited a stronger alpha ERS between 1 and 2 s compared to eyes open. For the remembered items, there was a significant cluster (clusterstat=1401; $p=0.02$) between 1 and 2 sec (Figure 5.3c). For the forgotten items, there was a significant cluster (clusterstat=1714; $p=0.002$) also between 1 and 2 sec (Figure 5.3f).

To visualize the topography of these patterns the effect pattern was split in three different half-second time windows: the first one from 0.5 to 1 s (see Figure 5.4), where the strongest alpha ERD is present for the subsequent memory comparison; a second, transitional time window from 1 to 1.5 sec (see Figure 5.5) where the alpha ERD is still present for the subsequent memory comparison but there is also strong support for an alpha ERS in the eye-closure comparison; and a third one, from 1.5 to 2 sec (see Figure 5.6) where the alpha ERS strongly supported in the eye-closure comparison, with less strong support for the alpha ERD effect in the subsequent memory comparison.

The topography plots show that the memory effect in the initial period (0.5 to 1 sec) appears as an alpha ERD spread across almost all the sensors, but with the main focus on the temporal sensors, especially right temporal sensors (see Figure 5.4 g and h). The effect appears to be due to either greater ERD or less ERS for later remembered items, depending on the sensor location. As time evolves, the alpha ERD only remains on the temporal sensors of both hemispheres (see Figures 5.5 g and h as well as 5.6 g and h). In contrast, the eye-closure ERS effect is mainly found at posterior and parietal sensors (see Figures 5.4, 5.5 and 5.6, c and f). Although the topography is maintained across time, the magnitude of the effect increases in the later time intervals.

Restricted Oscillatory Power Analysis

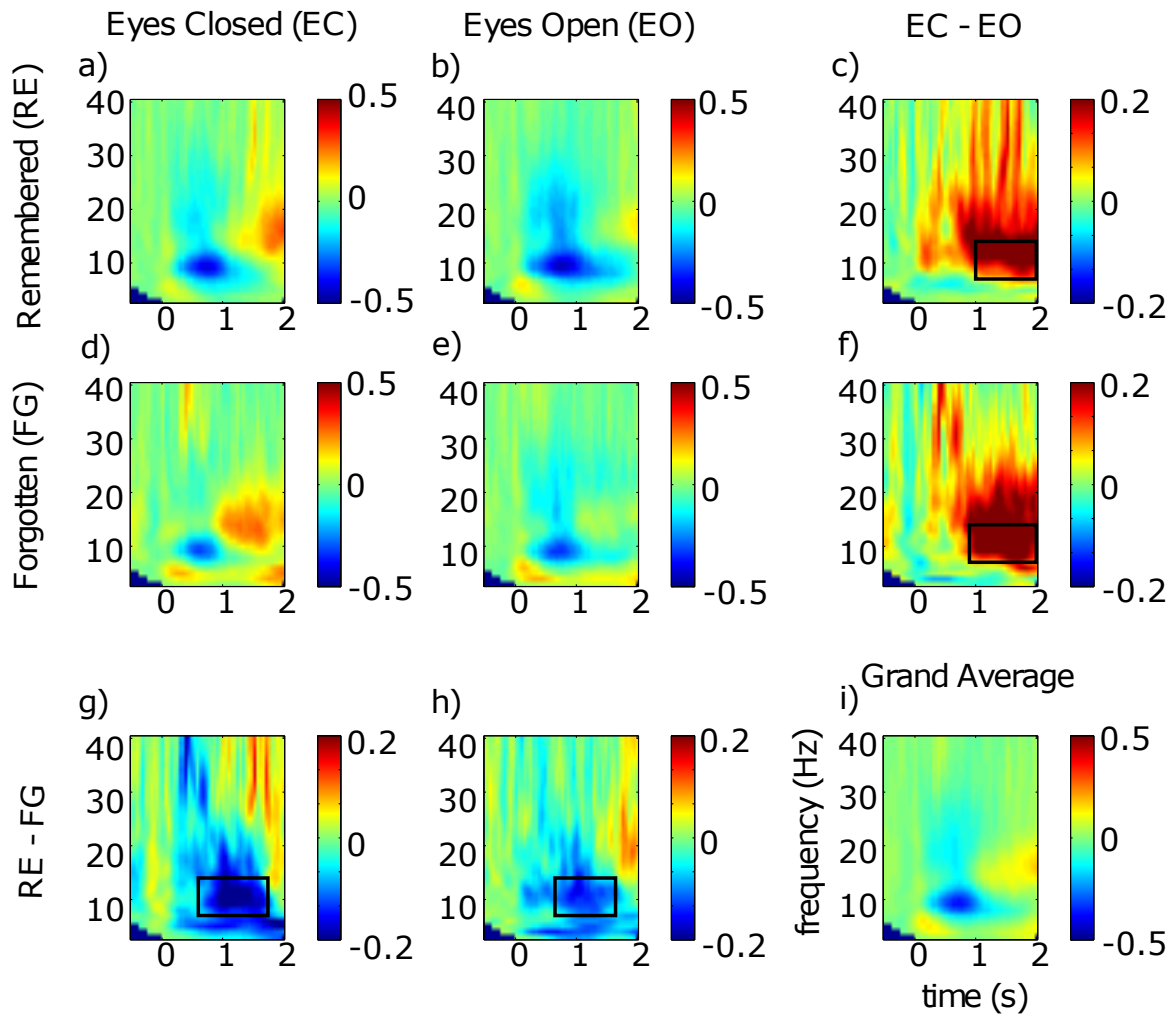


Figure 5.3: The power change relative to baseline (-0.5 - 0) s for the retrieval phase as a function of frequency and time. The first row shows power changes for remembered items, and the second row for the forgotten items. The first column shows power changes for eyes closed, and the second column for eyes open. The third row and column show the respective differences across eye closure and item status respectively, and the time-frequency plot on the right bottom corner shows the grand average across items and conditions. Cooler colors denote power ERD and warmer colors denote power ERS.

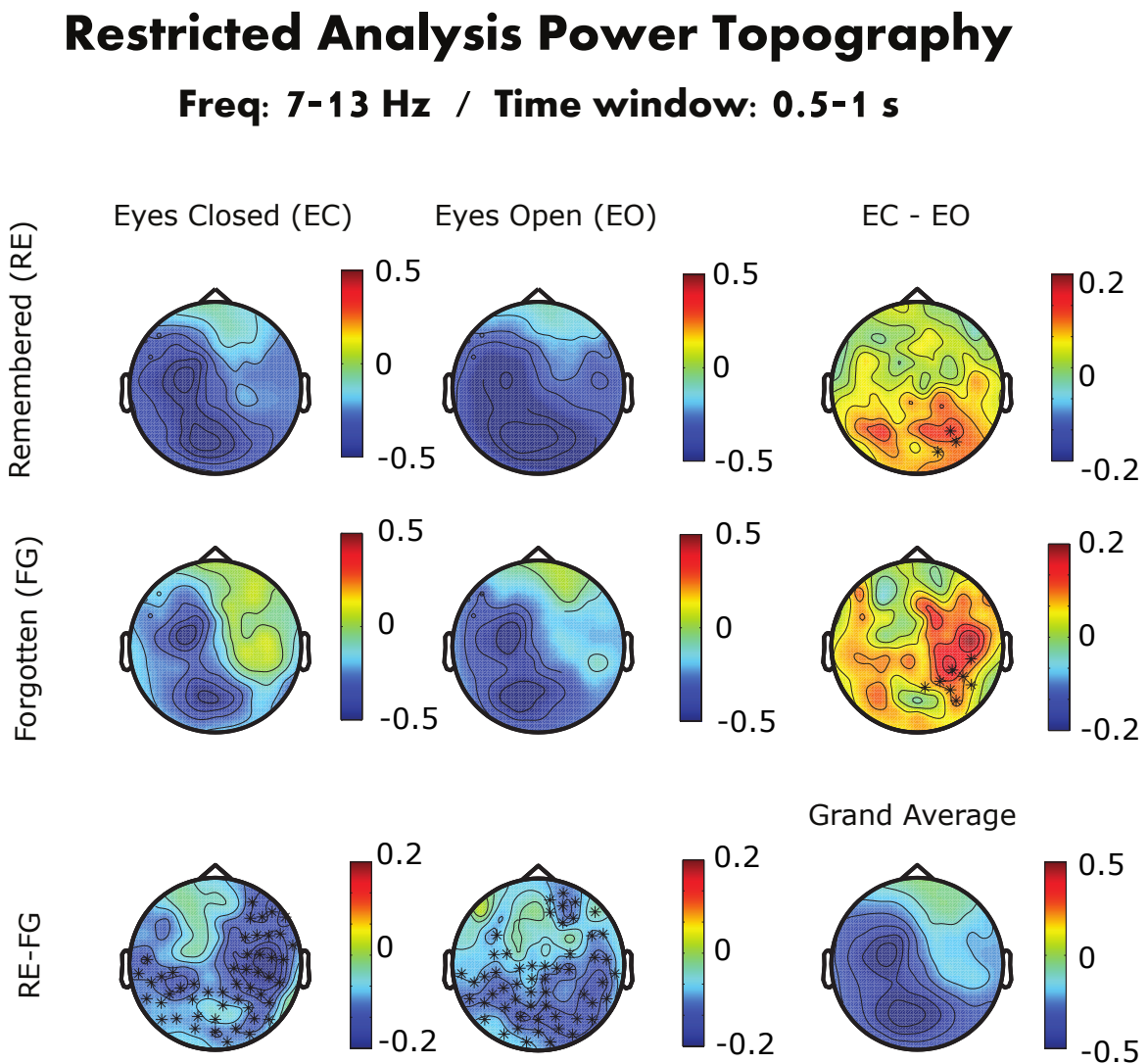


Figure 5.4: Topography of alpha (7 - 13 Hz) band power between 0.5 and 1 s. The layout of each of these figures is the same layout as Figure 5.3. Each topography plot shows the relative to baseline power change for the alpha band (7 - 13 Hz) over combined planar gradiometer sensors. The bold stars denote the sensors that were part of the cluster for each comparison. Color scale is the same as in Figure 5.3.

Restricted Analysis Power Topography

Freq: 7-13 Hz / Time window: 1-1.5 s

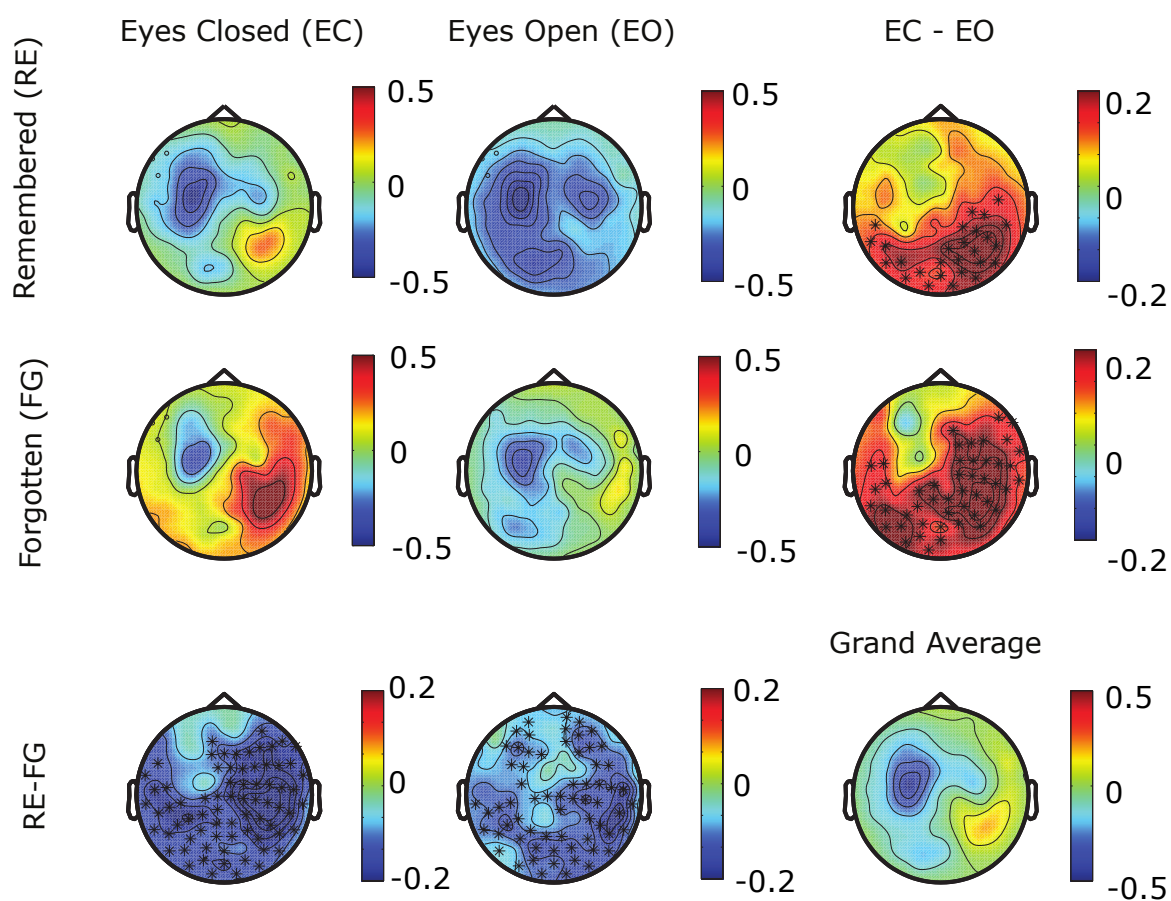


Figure 5.5: Topography of alpha (7 - 13 Hz) band power between 1 and 1.5 s. Layout is similar to 5.4.

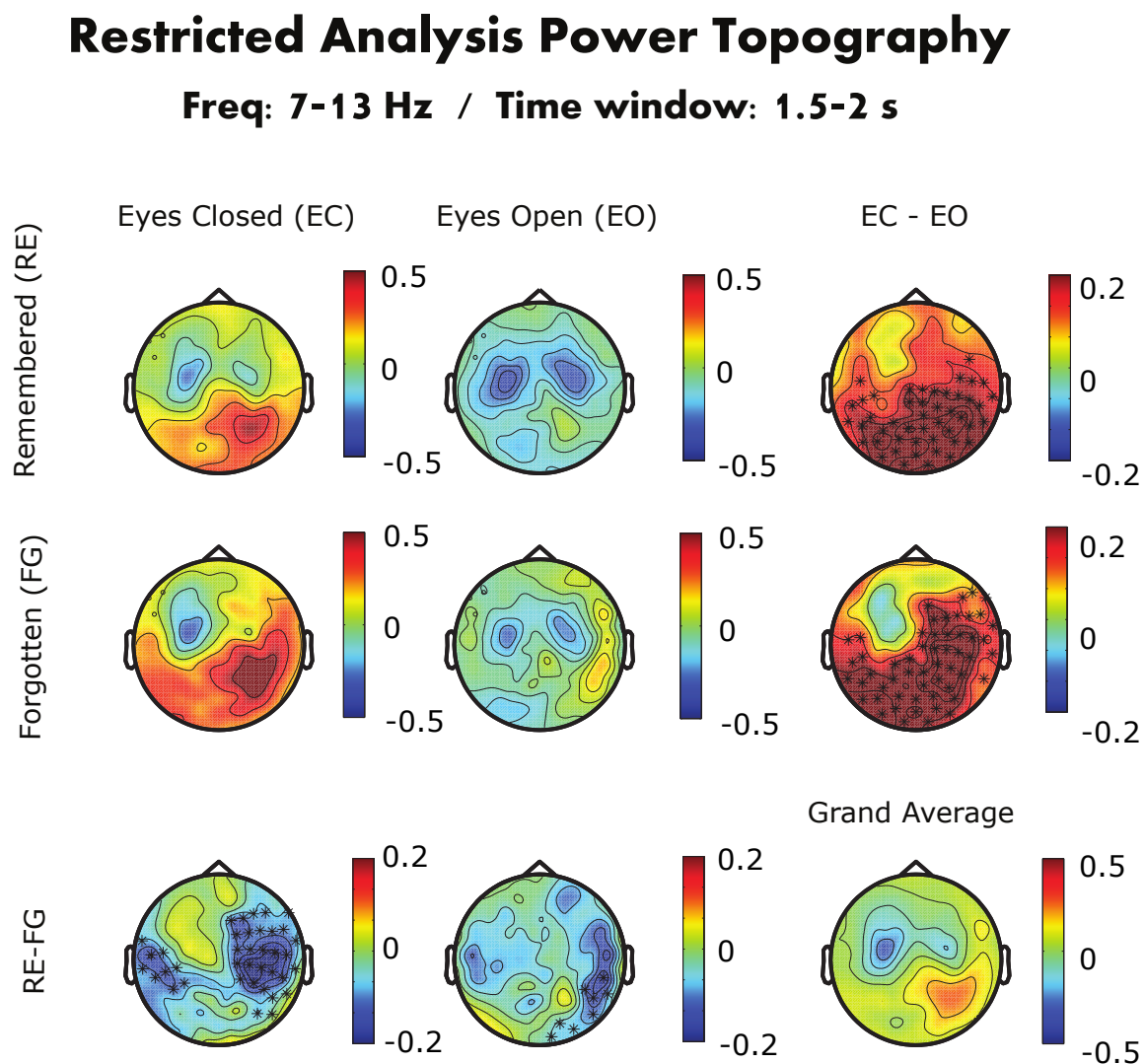


Figure 5.6: Topography of alpha (7 - 13 Hz) band power between 1.5 and 2 s. Layout is similar to 5.4

Statistical analyses were performed to test interactions. One analysis tested the modulation of eyes closed (Eyes closed vs Eyes open) on the item type effect (Remembered – Forgotten). The other analysis tested the modulation of item type (Remembered vs Forgotten) on the eyes closed effect (Eyes closed-Eyes open). Both analyses did not reveal any statistically significant cluster ($\text{abs}(\text{clusterstat}) < 259$; $p > 0.7$).

Unrestricted statistical analysis

For the unrestricted frequency analysis, the analysis schema of the a priori analysis was maintained, but, instead of focusing only on the alpha band, all frequencies from 3 to 40 Hz were included. Figures 5.7, 5.8, 5.9 and 5.10 are the equivalents to Figures 5.3, 5.4, 5.5 and 5.6, respectively.

The results were similar to the restricted alpha band analysis: remembered items showed a greater alpha ERD compared to forgotten items, for both eyes closed and eyes open condition. For the eyes closed condition, the statistical analysis revealed a cluster ($\text{clusterstat} = -8281$; $p = 0.002$) in a 4 - 27 Hz band, during the 0.65 - 1.8 s time window (see Figure 5.7g). For the eyes open condition, the analysis revealed a cluster ($\text{clusterstat} = -7357$; $p = 0.004$) in a 4 - 22 Hz band, during a 0 - 2 s time window (see Figure 5.7h). Note that although the cluster spans a large time window this is only true for the low frequencies around theta. For the rest of the frequencies the time window approximately overlaps the time window of the eye-closure effect.

An eye closure effect similar to the a priori analysis was also found, but it included a wider range of frequencies. For both types of items (remembered and forgotten) the eyes closed condition elicited a stronger alpha ERS between 0.6 and 2 s compared to eyes open, but in addition, the effect included beta ERS. For the remembered items, the statistical analysis supported a significant cluster ($\text{clusterstat} = 14766$; $p = 0.01$) between 8 - 38 Hz, over the interval of 0.6 - 2 s (Figure 5.7c). For the forgotten items, there was a cluster ($\text{clusterstat} = 13840$; $p = 0.006$), between 7 - 27 Hz, over the interval of 0.8 - 2 s (Figure 5.7f). This analysis revealed that, in addition to the alpha band, the beta band during the retrieval phase is also modulated by eye closure. Moreover, the time windows of the memory effect and eye-closure effects seem to overlap more than in the restricted analysis.

In the early phase the memory effect is mainly found in the alpha band as a greater ERD or reduced ERS for remembered items compared to forgotten items, for both eyes closed and eyes open conditions. Compared to the restricted analysis, it includes part of the beta band. Similarly to the restricted analysis, the biggest magnitude of the effect is found on right temporal sensors (see Figures 5.8, 5.9 and 5.8, g and h). On

Unrestricted Oscillatory Power Analysis

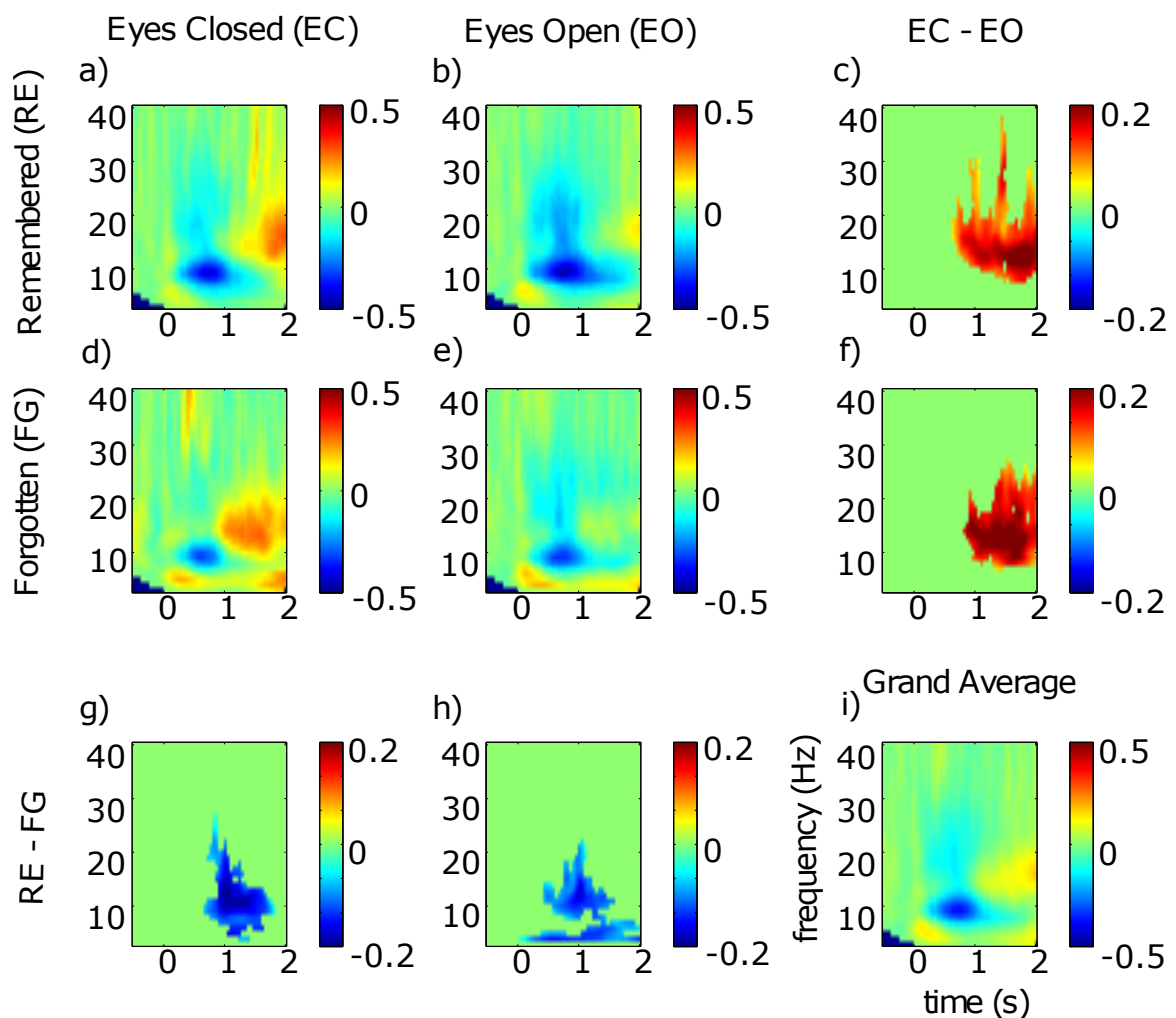


Figure 5.7: Oscillatory power analysis of the retrieval phase. Layout is similar to Figure 5.3. Plots (c),(f),(g) and (h) show only the time-frequency points that were part of a cluster with statistical support.

Unrestricted Analysis Power Topography

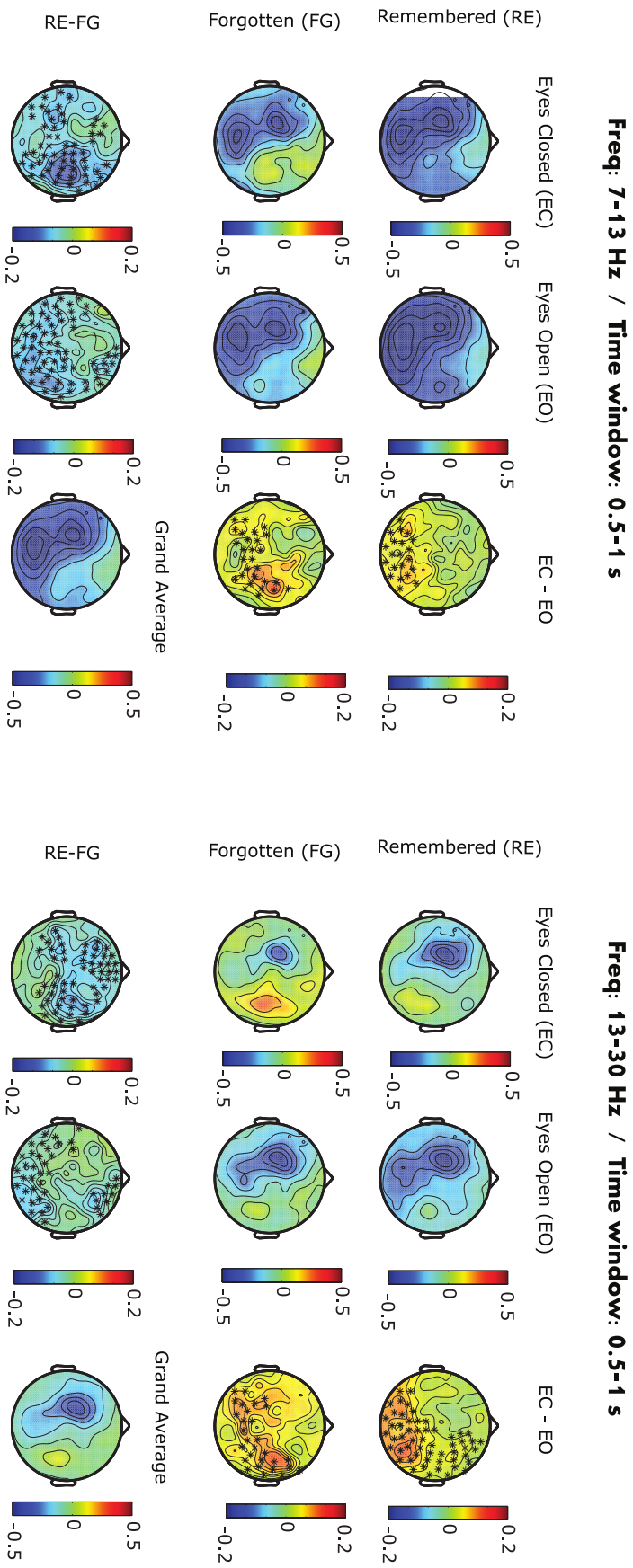


Figure 5.8: Topography of the relative power changes for alpha (7 - 13 Hz) and beta (13 - 30 Hz) between 0.5 and 1 s. The left layout (a) shows alpha band (7 - 13 Hz) power. The right layout (b) shows beta band (13 - 30 Hz) power. In each layout, first row represents the remembered items, and the second row the forgotten items. The first column, represents the eyes closed conditions and the second the eyes open condition. The third row and column show the respective differences, and the topography plot on the right bottom corner shows the grand average across items and conditions.

Unrestricted Analysis Power Topography

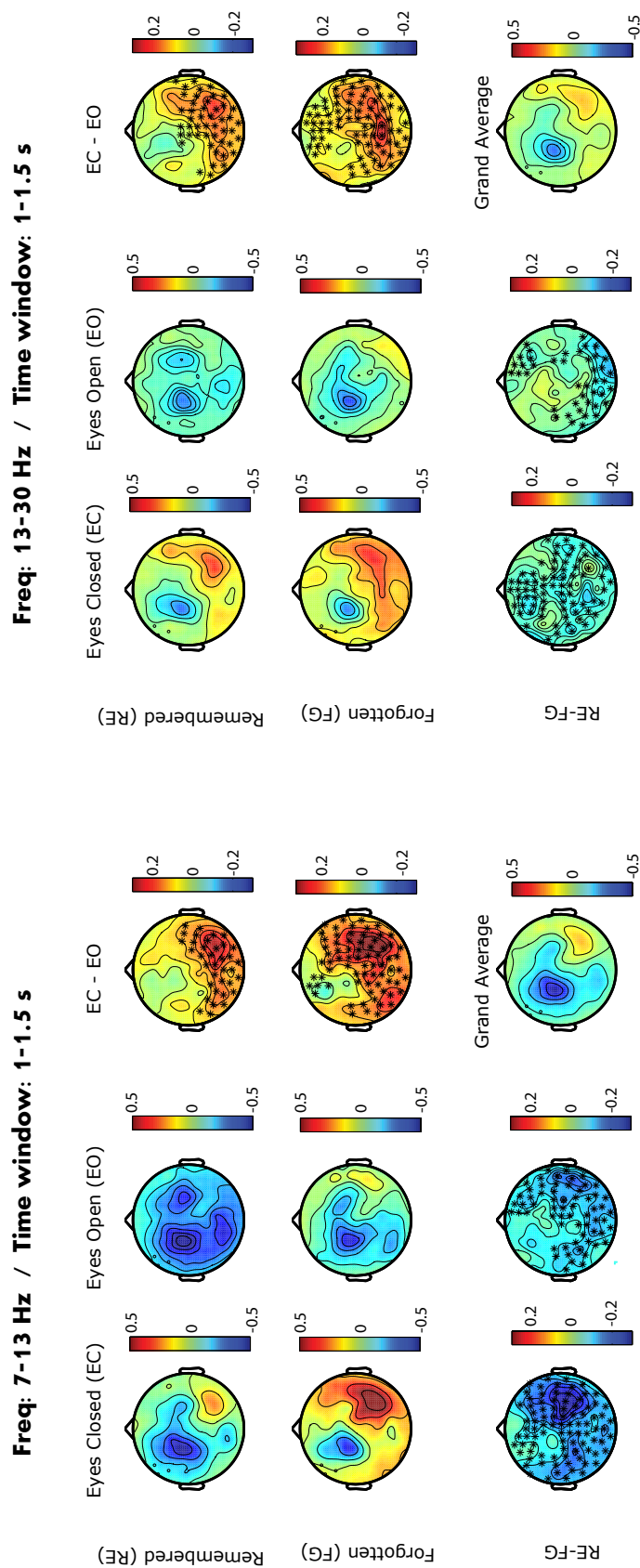


Figure 5.9: Topography of the relative power changes for alpha (7 - 13 Hz) and beta (13 - 30 Hz) between 1 and 1.5 s. The layout is the same as Figure 5.8.

Unrestricted Analysis Power Topography

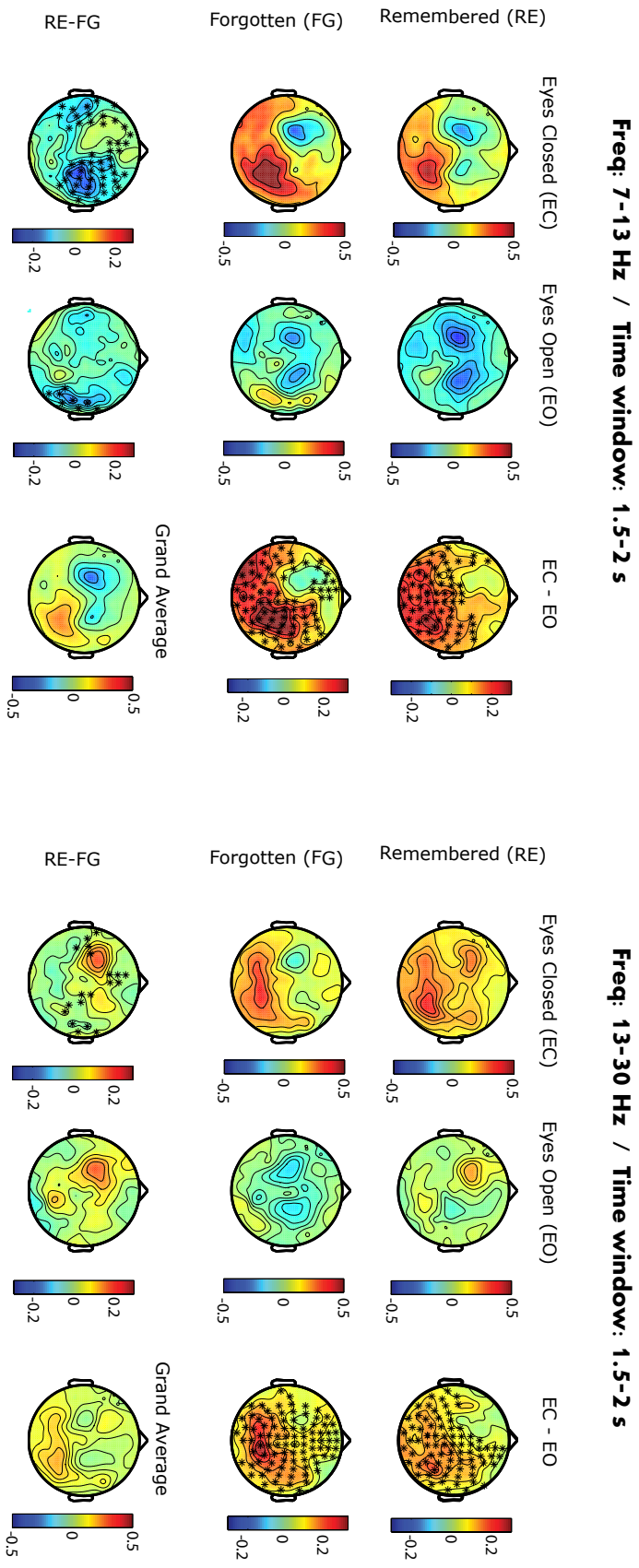


Figure 5.10: Topography of the power during alpha (7 - 13 Hz) and beta (13 - 30 Hz) between 1.5 and 2 s. The layout is the same as Figure 5.8.

the other hand, the eye-closure effect is equally found in alpha and beta bands, as a greater ERS for eyes closed compared to eyes open. The effect is mainly found in posterior and right-parietal sensors (see Figures 5.8, 5.9 and 5.10, c and f).

Statistical analyses were performed to test for interactions (the same as the a priori analysis). Similar to the restricted analysis, the results did not reveal any significant cluster ($\text{abs}(\text{clusterstat}) < 259$; $p > 0.71$).

Source level analysis

Figures 5.11, 5.12 and 5.13 illustrate the results of the power analysis at source level for each of the time window.

The grand averages of the three time windows show an overall brain desynchronization of the alpha rhythm (7-13 Hz), although the main rhythm desynchronization occurs in the left motor areas.

Comparing the different conditions, the data are partially consistent with the sensor level analysis. In the first time window (0.5 - 1 s) the statistical analysis only showed differences between forgotten and remembered words for the eyes open condition (see Figure 5.11). The cluster was localized in the right posterior inferior temporal and right occipital lobes ($\text{clusterstat} = -684.17$; $p\text{value} = 0.035$).

In the second time window (1 - 1.5 s) the statistical analysis captured both item and eye-closure effects (see Figure 5.12). For the eyes-opened condition remembered words show greater alpha ERD in the left IFG, posterior STG and angular gyrus ($\text{clusterstat} = -889.23$; $p\text{value} = 0.017$). For the eyes-closed condition remembered words show greater alpha ERD in the right parietal and frontal lobes ($\text{clusterstat} = -1155.2$; $p\text{value} = 0.008$). Eye-closure showed less alpha ERD than eyes-opened condition in the occipital and posterior-parietal lobes was found in the remembered words ($\text{clusterstat} = 645.15$; $p\text{value} = 0.049$).

In the third time window (1.5 - 2 s) the statistical analysis showed only an eye-closure effect (see Figure 5.13). Both remembered and forgotten words showed eye-closure showed less alpha ERD than eyes-opened condition in the occipital and posterior-parietal areas ($\text{clusterstat} = 2931.1$; $p\text{value} < 0.001$ and $\text{clusterstat} = 1184.5$; $p\text{value} = 0.005$ respectively).

Statistical analyses were performed to test for interactions (the same as in the previous two analyses). The results did not reveal any significant cluster ($\text{abs}(\text{clusterstat}) < 222.94$; $p > 0.18$).

Source-level Power Analysis

Freq: 7 - 13 Hz / Time window: 0-0.5 s

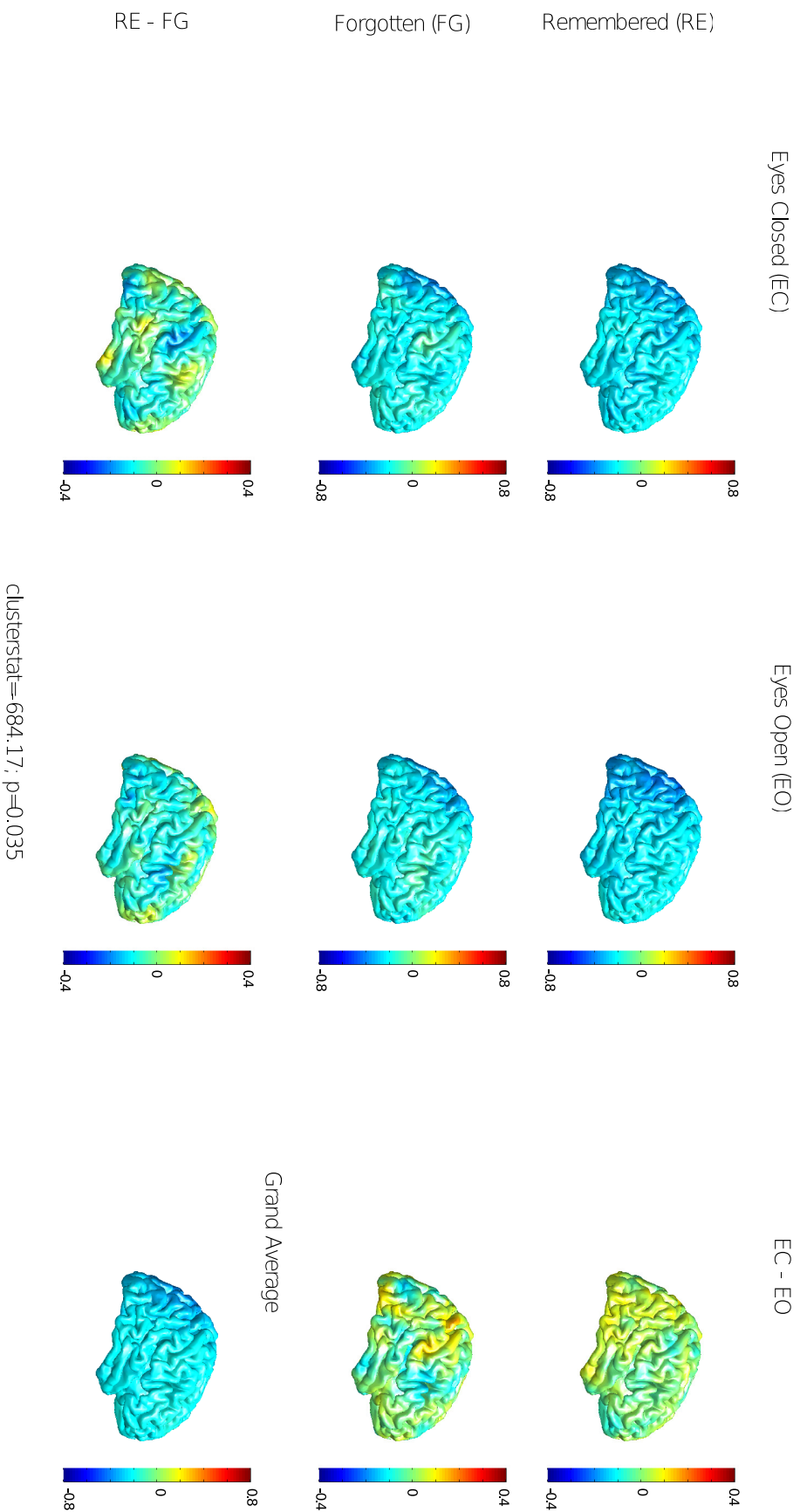


Figure 5.11: Source reconstruction for alpha (7 -13 Hz) between 0.5 and 1 s. Fourth row and column show the localization of the clusters that statistically show differences between conditions. The layout is the same as Figure 5.8.

Source-level Power Analysis

Freq: 7- 13 Hz / Time window: 1-1.5 s

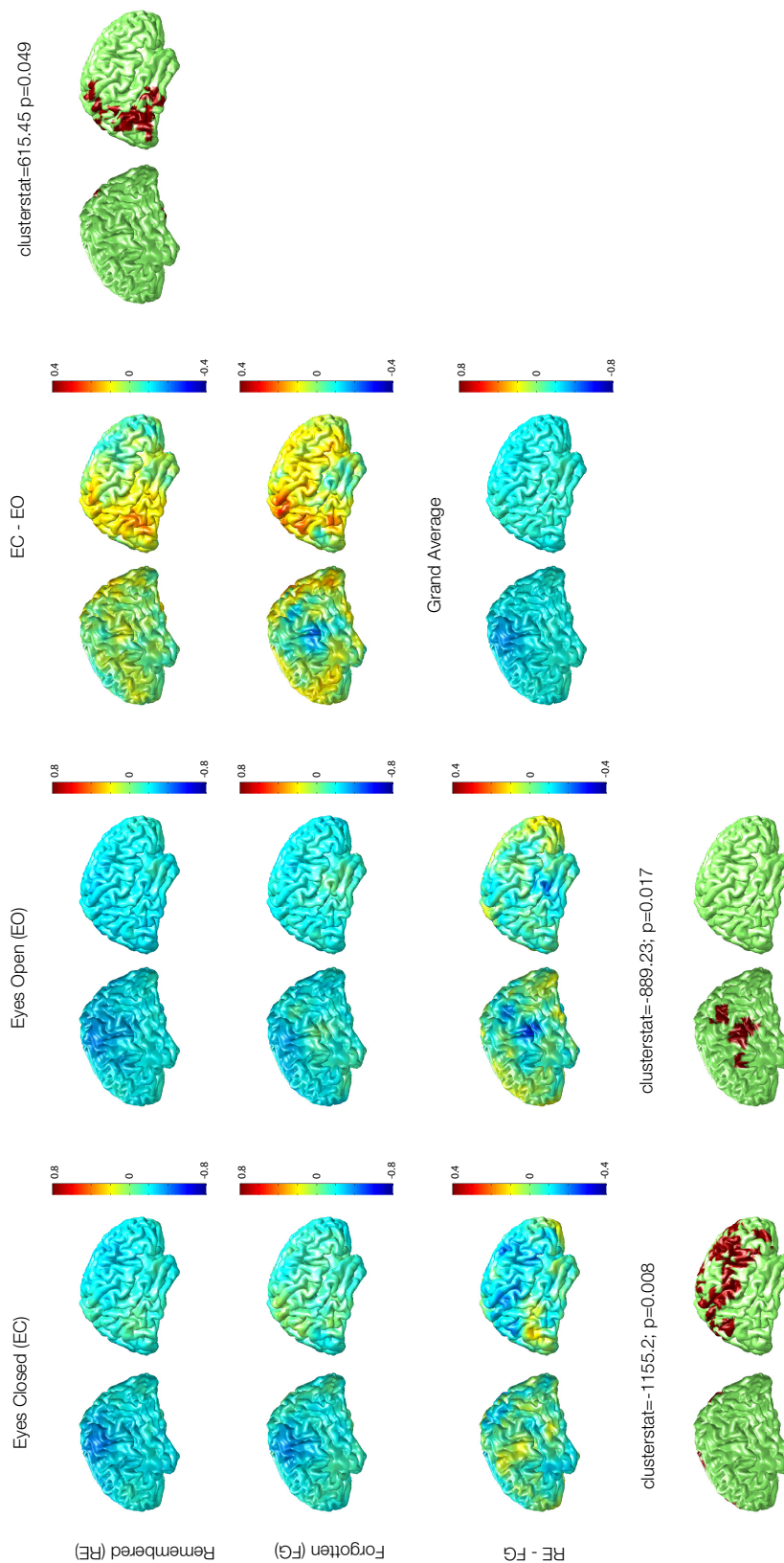


Figure 5.12: Source reconstruction for alpha (7 -13 Hz) between 1 and 1.5 s. Fourth row and column show the localization of the clusters that statistically show differences between conditions. The layout is the same as Figure 5.8.

Source-level Power Analysis

Freq: 7 - 13 Hz / Time window: 1.5-2 s

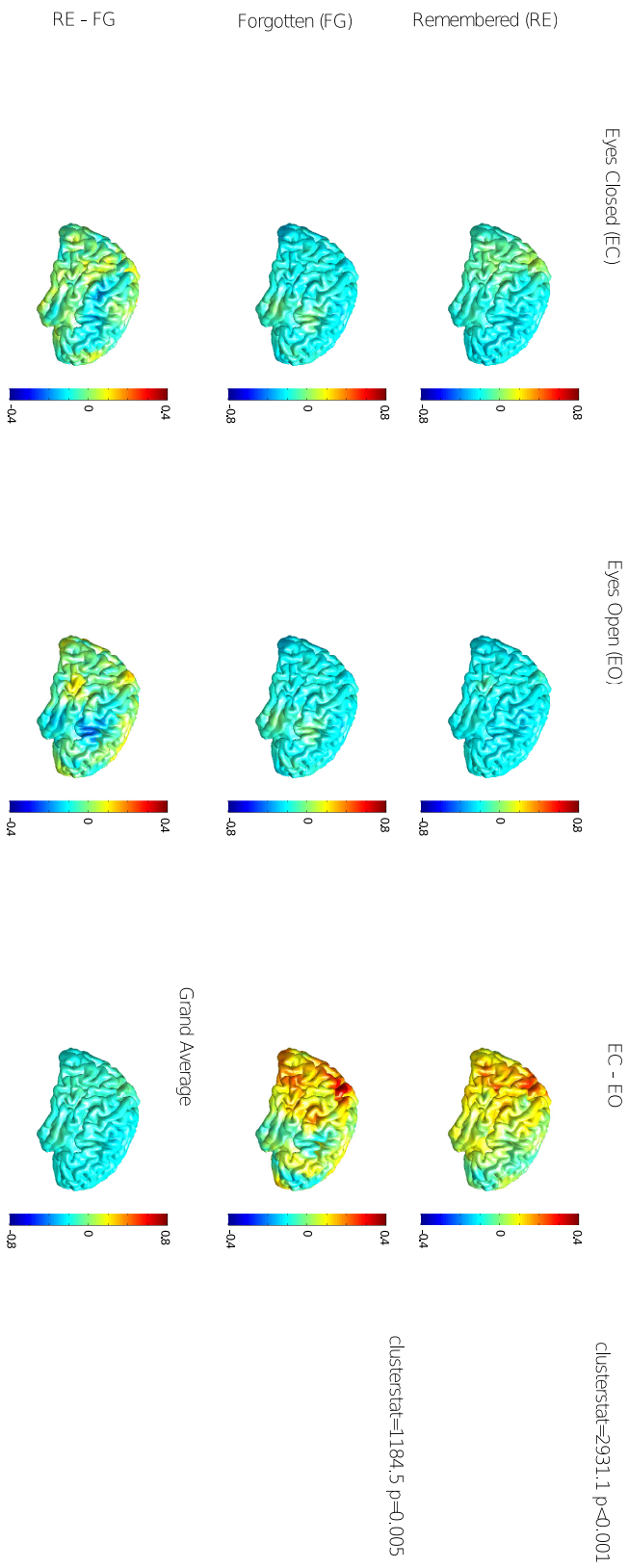


Figure 5.13: Source reconstruction for alpha (7 -13 Hz) between 1.5 and 2 s. Fourth row and column show the localization of the clusters that statistically show differences between conditions. The layout is the same as Figure 5.8.

5.5 Discussion

In this experiment, participants recognized spoken words in a recognition memory task conducted in the MEG either with their eyes open or their eyes closed. Several analyses of the oscillatory power of the MEG signals recorded in the task showed that successful memory was associated with greater alpha-band desynchronization for a half-second interval after word presentation. In contrast, eye closure was associated with greater alpha and beta-band synchronization for a later interval after word presentation. No evidence of a behavioral effect due to eye closure was found. Similarly, for both alpha-ERD and high-alpha/beta-ERS, no statistical support for an interaction between eye closure and item type effects was found. Nonetheless, the classical alpha increase in posterior sensors due to eye-closure was found during the separate resting state recording.

The restricted analysis was conducted to test the hypothesis that power in the alpha band would be modulated by both eye-closure and type of item during the memory task, and to test for the possible interaction of these two modulations. Moreover, an unrestricted-frequency analysis was conducted to explore whether the effects found on the first analysis were biased (or not) due to the restrictions of the frequency range. When both analyses were compared, modulations of the ERD due to type of item (remembered vs. forgotten) found in the restricted analysis we also encountered in similar frequency bands, time windows and sensor locations in the unrestricted analysis. On the other hand, the eye-closure alpha modulation effect is more spread (including also beta frequencies) when an unrestricted analysis is performed. Therefore, when combining results of both analysis, it is assumed that the modulations of alpha ERD due to items in both analyses are reflecting the same reduction in alpha power, and that the eye-closure ERS modulation observed during the task is an increase in power for both the alpha and beta bands. Hence, the results of both analyses are interpreted to reflect the same effects and, therefore, discussed together in the following paragraphs.

Previous studies have shown that during the retrieval phase of a memory task, when the presented stimulus is to be categorized as new or old, alpha desynchronization occurs in response to the stimuli (Klimesch, 1999; Schack and Klimesch, 2002; Klimesch et al., 2003). Moreover, better performance has been linked to greater alpha ERD (Klimesch et al., 1997; Klimesch, 1999; Doppelmayr et al., 2005; Hanslmayr et al., 2005). Data from this experiment also demonstrated the expected memory effect: alpha decrease was larger for remembered items than for forgotten items. However, previous EEG studies reported an alpha modulation on electrodes consistent with posterior sources, while the effects found in this study

also included MEG temporal (planar gradiometer) sensors. The source level analysis located the effect in the left superior temporal and IFG areas for the eyes open condition. For the eyes-closed condition the effect was found in the right parietal and frontal lobes. While the localization difference between previous studies and the present experiment might reflect differences in the overall sensitivity of EEG and MEG, there is also an additional explanation.

While the previously-mentioned studies used visual stimuli, this study presented auditory stimuli to the participants in order to be able to study the potential effects of eye closure on retrieval. Note that Krause et al. (1996) also tested auditory memory, and that even though they found alpha ERD in response to stimuli in the retrieval phase, alpha ERD was not modulated by performance. In his review Klimesch (1999) suggested that Krause and colleagues may have not found the effect that has been reported in the visual domain because auditory stimuli could be modulating the tau rhythm rather than the alpha rhythm. Klimesch suggested that EEG is less sensitive to the tau rhythm (Klimesch, 1999), furthermore, pointing out that when MEG is used alpha rhythm modulations during auditory memory can also be seen in temporal sensors (Kaufman et al., 1992). Furthermore, recent studies have shown that greater alpha ERD for remembered items is found in the sensory region of the to-be-attended modality (temporal regions for auditory modality, posterior regions for visual) (Jiang et al., 2015).

The fact that this experiment used auditory stimuli and the effects were mainly found in temporal sensors suggests that results are showing a tau rhythm modulation. Moreover, for the eyes opened condition the effect was localized in areas that are part of the language network.

What is the theoretical implication of the different labels associated with these 10-Hz rhythms? It may be that the functional role of a given modulation (e.g., ERS or ERD) of a rhythm depends not only on the frequency range and time interval, but also the specific brain network that is responsible for generating the rhythm. The role of a 10-Hz modulation of a posterior, visual-cortex rhythm may not be the same as a modulation of a 10-Hz temporal, auditory-cortex rhythm, for example, even if the physiological implementation of the modulation is similar in the two cases.

In this work, two types of modulations due to eye-closure were found. The first one would be the "classical" alpha increase due to eye-closure during resting state. This alpha increase is also present, but in smaller magnitude, during the retrieval phase (e.g., see Figure 5.2). The second modulation due to eye-closure is the modulation in the alpha and beta bands of the evoked-power in response to the stimuli. In both bands the ERS effect was greater in the eyes closed condition

compared to the eyes open condition at occipital and right parieto-temporal sensors. The alpha band eye-closure effect was source localized in the occipital and posterior-parietal areas, for both remembered and forgotten items. While the alpha modulation due to eye-closure might be expected based on the frequently-observed association between eye closure and higher absolute posterior alpha power, a modulation of (evoked) beta power due to eye-closure has not been reported so far in the literature.

As a methodological aside, it should be noted that the comparison between eyes open and closed conditions involves a difference in baseline power, in addition to any post-stimulus changes in power. This baseline difference complicates the interpretation of the relative power changes because it creates an ambiguity: observed differences could be due to either a difference between baseline and active-period spectral power, or it could be influenced by the absolute difference in baseline spectral power itself. However, the greater beta-ERS seen in the eyes closed condition is a larger relative change from a baseline that already has larger spectral power (e.g., Figure 5.2). That implies that the power difference in the eyes closed ERS is larger in absolute terms than in the eyes open condition.

One possible interpretation of the ERS effect would be that the beta-ERS is an extension of the alpha-band eye-closure effect. In other words, the effect is due to a broadening of the spectral peak when alpha band power increases to include the neighbouring bands (theta and beta). Barry et al. (2007) reported a similar modulation in the beta-band when they studied the effect of eye-closure in different frequency bands during resting state: Higher beta-band power was found for eyes closed in posterior and right parietal EEG electrodes.

On the other hand, one might also explain the beta-ERS as a post-movement beta-rebound (Pfurtscheller et al., 1996, 1998). After motor activity, power in the beta band of motor cortex shows an ERS. In this scenario, the modulation of the beta-ERS would be linked to somatosensory or motor differences between conditions. Different studies reported that beta-rebound can be modulated by different factors, for example, the force of a movement (Fry et al., 2016) or the correctness of an observed action (Koelewijn et al., 2008). To the best of our knowledge, no study has compared the beta-rebound with and without eyes-closed. However, it is plausible that a finger movement to press a button can be different with eyes open (providing visual feedback for our movement) compared to eyes-closed (no visual feedback). This difference could explain the beta-band modulation seen in this experiment. Although this explanation is speculative, it would be possible to investigate this issue with future experiments comparing simple movements with and without eye closure. The main drawback of this last motor explanation is that the

beta-ERS modulation seen here was mainly found in posterior sensors and not on sensors closest to motor cortex. Moreover, the topography of the beta increase is more similar to the classical alpha eye-closure effect, as well as to the topography reported by Barry et al. (2007). Therefore, we suggest that the beta-ERS modulation due to eye-closure observed in this particular study is more likely to be an extension of the alpha-band eye-closure effect.

How does eye closure affect alpha (or tau)? Perhaps the most striking feature of the current data set is that the dynamics of alpha/tau-band in the evoked-power responses do not show a greater ERD of the evoked response due to eye-closure, but rather a later ERS for both alpha and beta. Although one would expect an alpha modulation for eye-closure, it is important to note that the evoked response to an auditory word is activity related to perception and word comprehension. In contrast to the differences shown in the absolute power during resting state, the results here indicate the dynamics of the different bands in response to a word, and here, eye-closure seems to relate to late ERS. Furthermore, eye-closure was not associated with either a benefit or an impairment in the behavioural performance. This reinforces our intuition of tau being the rhythm that is modulated by the memory effect in this paradigm and posterior alpha-beta being modulated by eye-closure, with no direct interaction between them. On the other hand, the source level analysis of the data showed that eye closure modulated the localization of the remembered vs. forgotten effect: with eyes open the effect is found in the language network and with eyes closed in the right parietal and frontal lobes. However, no difference was found when interactions were tested statistically.

The results of the present experiment agree with the modality-specific interference theory, which suggests that reducing visual interference by closing the eyes promotes visualization of the event and potentially improves memory, but would not help memories of other modalities (Vredeveldt et al., 2011, 2012). In this case, the material that participants had to encode was of a linguistic nature. Recalling this material in the retrieval phase would rely on the language network encompassing bilateral speech perception areas and left perisylvian language areas. Based on the oscillatory analysis results, it appears that modulating posterior alpha by closing the eyes does not directly affect the processing efficiency of the language network, and as a result there was no improvement or detriment of the memory performance due to eye-closure in this task.

Note that this explanation could in principle be tested with orthogonal conditions, although it is difficult to envision a design that would involve ear-closure, or visual stimuli that can be presented during eye-closure. Therefore, we suggest that more research should be done in order to clarify the independence or

interactions of the different rhythms in the brain, and try to use them to understand how modality specific improvements and general load suppression could enhance different cognitive processes.

5.6 Summary

In this experiment the expected memory effect was found: greater alpha ERD for remembered words compared to forgotten words. This effect was found mainly on temporal sensors rather than in posterior sensors. The source level analysis localized the effect in the language network and in the right parietal and frontal lobes. This is evidence that auditory or spoken linguistic stimuli modulate the tau rhythm while the eye-closure modulates the posterior alpha. The lack of interaction between both modulations in our experiment suggests that tau and posterior-alpha should be considered as two independent rhythms. This would explain why eye-closure did not enhance the memory performance of participants in this particular environment. The data also show that when focusing on short time interval measures, oscillatory changes are easier to identify. This might explain why the experiment described in Chapter 4 did not show large oscillatory modulations due to learning.

Part III

Discussion and final remarks

Chapter 6

General discussion and summary

The main goal of this thesis was to characterize language-related short-term learning changes in the adult brain. Previous studies have mainly used longitudinal and cross-sectional designs and therefore they captured brain responses of already consolidated rules. On the other hand, studies that used on line or lab training, and therefore captured short-term changes, were conducted in EEG and provided no source correlates related to these changes. However, short-term and long-term learning seem to elicit different plastic changes (Rossini and Melgari, 2011), hence, the anatomical-correlates of the MEG experiments carried out in this thesis provide useful information to better understand which plastic changes occur in short-term learning. Subsets of natural languages (miniature languages) were used in two of the experiments in order to study short-term changes. It was hypothesized that miniature languages allow us to capture language-related changes without the need of course-like long-lasting training. The third experiment was a memory task in the participants' native language, and aimed to provide a better understanding of physiological memory functions, especially the role of oscillations in memory retrieval.

6.1 Summary of results

In Chapter 3, grammar learning was tested using a violation-control judgement task that allowed the MEG to assess the brain's activity at a very short time scale. Accuracy rates and MEG signals were recorded prior, during and after training and compared to recordings of the same task in the participants' L1. The results showed that, before training, participants were not able to correctly judge noun phrases. In contrast, from the first training block participants were highly accurate on the judgment and maintained this performance on the generalization test. The network involved in the processing of the violation changed with training. In the first training

block, the network was localized at right fronto-parietal lobes and temporal lobe. By the last training and generalization blocks, the network was localized in left temporal lobe and inferior-occipital gyri, which approximates to the network observed in L1.

In Experiment 2, language learning was tested using a sentence-listening task. Participants listened to sentences in both their native and a non-known language while MEG signals were recorded. The same task was performed before and after training in the non-native language. In this experiment the oscillatory responses to sentence listening were analyzed. Power changes were found in the language network both when listening to the native and the novel-language, although power changes were larger in the novel-language (this finding may be confounded with block order). No strong evidence was found for oscillatory power modulation due to language learning.

In Experiment 3 auditory memory-retrieval in L1 was tested in order to better understand oscillatory activity that underlies memory retrieval. It was hypothesized that participants would recognize more words when retrieval blocks were performed with eyes closed than with eyes open. However, eye closure did not modulate the behavioural performance. Regarding the MEG recordings, eye closure elicited the expected alpha increase on parieto-occipital sensors. However, alpha power modulations due to remembered or forgotten words were found at temporal sensors (tau rhythm). Moreover, no interaction was found between alpha and tau rhythms.

6.2 How are brain networks modulated in short-term learning?

Previous studies have demonstrated that ERP measures can be more sensitive to capture learning changes than behavioural measures (Kotz and Elston-Güttler, 2004; Mueller, 2005). In agreement with this observation, the experiment described in Chapter 3 showed that even if behavioural measures were stable across training blocks, the ERF modulations varied. Moreover, the experiments presented in this thesis captured different types of functional brain changes. On the one hand, results from Chapter 3 illustrate that the brain regions recruited for performing the task change with training. On the other hand, Chapters 4 and 5 capture power modulations within the same brain regions.

In the experiment of Chapter 3, for instance, during the first training block the grammaticality effect was located at right fronto-parietal and temporal lobes. Right frontal areas have been previously associated with non-syntactic specific error

detection processes (Indefrey et al., 2001). Moreover, based on the hemispheric encoding/retrieval asymmetry (HERA) model, right frontal areas are related to memory retrieval processes (Habib et al., 2003). Nonetheless, after just a few minutes, during the second training block a grammaticality effect was located at left parieto and temporal areas. During the third training block the effect was localized at left temporal lobe. The fact that for the last two training blocks the effect is localized in the language network suggests that the new L2 memories are already being created and embedded in language related regions and not in separate regions responsible for other cognitive processes. These network changes can be interpreted as a transition to a stage of 'grammaticalization', a stage where learned rules are instantiated in the learner's real-time language processing system (McLaughlin et al., 2010).

Although these results from Chapter 3 are in line with studies on short-term language learning (Mueller et al., 2008, 2007, 2005; Davidson, 2010; Davidson and Indefrey, 2009a), at first sight they are less congruent with longer-term language learning studies. These results indicate that brain networks adapt to process the new skill rapidly and that after minutes the new skill relies on a network that resembles the network in L1, even if it is not completely overlapping. Nevertheless, longitudinal studies have shown that participants within the first year of formal training do not show native-like patterns (McLaughlin et al., 2010). One possible explanation would be that, while short-term studies use focused training of small fragments of language and test participants on that specific fragment, in longitudinal studies participants acquire a variety of language features but are tested only on an small fragment of language. Therefore, it might occur that the fragment they are tested on is still not completely 'grammaticalized' (McLaughlin et al., 2010). Another possible explanation is that rapid changes that occur during short-term learning might not result in long-lasting changes unless the training is maintained. Results from this experiment also indicate that even when ERF effects' timing and shape show a similar pattern, source reconstruction is sensitive to changes that are harder to detect at the sensor level. Moreover, as a result of the source reconstruction analysis brain network changes related to the ERFs were identified. Therefore, due to its improved spatial resolution (Baillet, 2017), MEG offers an advantage versus EEG for measuring language related brain plasticity.

Regarding the experiment described in Chapter 4, no clear evidence of oscillatory power modulation due to learning was found. Nevertheless, this does not necessarily indicate a lack of brain plasticity. It might be the case that the analysis performed on the data is not capturing brain changes that occurred. The presented analysis focused on long periods of oscillatory activity which captured many cognitive functions that occur during sentence listening. Focusing on short time interval measures might

reveal oscillatory activity changes, as shown in Chapter 5. On the other hand, it might be the case that the training session was not sufficient to provoke oscillatory changes. Whereas the experiment in Chapter 3 reflects a fast embedding of the acquired knowledge, this is not the case for the experiment in Chapter 4.

At first sight, this is contradictory with previous studies suggesting that syntactic learning is more critical than semantic learning (Sanders et al., 2008; Birdsong, 2006). However, in the present experiment the acquired vocabulary was presented embedded in sentences. Sentence processing involves several cognitive tasks (e.g. speech segmentation), which could explain why brain changes due to sentence processing training in L2 need more time so that they can be observed in the MEG data. A third possibility is that oscillatory brain changes occur during training but do not last until the second MEG session. As was suggested for the experiment in Chapter 3, the duration of short-term brain changes due to language learning still remains understudied.

6.3 Is the language network recruited at the beginning of language learning?

A unceasing research question in the field of second language acquisition is whether processing L2 recruits the L1 language network and how the L1 and L2 processing brain networks overlap (see Indefrey, 2006, for a review of fMRI studies). In previous studies L2 learners or speakers have been compared with another group of L1 speakers of the tested language (see Caffarra et al., 2015, for a review of L2 EEG studies). Differently, in this thesis, the same group of participants was tested in both their L1 and newly acquired L2.

Although in Chapter 3 there was no direct comparison of L1 and different training blocks, a qualitative comparison of brain areas recruited in both languages can be explained as follows. From the second training block on, the raw difference between violation and control phrases is localized in areas of the left inferior frontal and temporal cortices that overlap with the existing models of the language network (Hagoort, 2016; Friederici, 2011). Nonetheless, statistical analysis only supported some brain regions within this network and the region varied from block to block. This partial overlap is consistent with a previous MEG longitudinal study where violation control effects were localized within the language network, but for each testing session the statistically significant region varied in location (Davidson and Indefrey, 2009b).

On the other hand, in Chapter 4 a whole-brain analysis localized an effect of language in frontal areas for the theta band and in bilateral temporal lobes for alpha and beta bands, which is consistent with the patterns reported in previous oscillatory analyses of L1 processing (Lam et al., 2016). Our results suggest that oscillatory dynamics are larger for the newly acquired L2 compared to the native language. It has been proposed that larger alpha desynchronization implies more information processing, while larger alpha synchronization denotes inhibition (Klimesch et al., 2007). Based on this, patterns from this experiment suggest that temporal areas require more processing for L2 speech processing, while the areas not processing speech are more inhibited than in L1. These findings are consistent with Indefrey (2006), who argued that L2 learners at initial stages need more effort to perform a task which is reflected in more strongly recruited brain areas. However, when a certain proficiency is attained those tasks become easier and, in turn, the patterns of brain activity are more similar to those observed in L1.

In summary, our results suggest that the language network is present from the beginning of L2 learning, although in a different manner than in L1. Moreover, Chapter 3 indicates that with sufficient training the network involved in a task in L2 starts to look similar to networks involved in L1. Similar hypotheses have been stated based on EEG studies that found ERP patterns in L2 evolve with training towards an L1-like pattern, although they are not identical (e.g. Mueller, 2005).

6.4 Concluding remarks

The main goal of this thesis was to characterize language-related short-term brain changes in adults. Previous studies have mainly used longitudinal and cross-sectional designs and therefore captured brain responses of already consolidated rules. On the other hand, the studies that used online or lab training, and therefore captured short-term changes, were conducted with EEG and provide no source correlate of those changes.

One of the strongest points of this thesis is that it shows that anatomical correlates of language learning can be measured with a non-invasive technique. The results revealed changes of these correlates within just a few minutes or hours. It is important to measure these anatomical correlates since, as Kotz and Elston-Güttler (2004) and Mueller (2005) suggested, electrophysiological measures can be more specific, and capture changes that behavioural measures do not. In line with these two works, Chapter 3 showed that the brain networks changed from block to block in a learning task while behavioural measures were stable. Moreover, it showed that source

reconstruction with MEG is more sensitive to some brain network changes that are less detectable at the sensor level.

Another important feature of this thesis is that it has been shown that just a few minutes of training are needed to see some electrophysiological changes. Although fast changes at the sensor level have been already shown (Davidson and Indefrey, 2009a, 2011; Mueller et al., 2005, 2007, 2008), until now source level changes were only shown after weeks of formal course training (Davidson and Indefrey, 2009b).

Moreover, to the best of our knowledge, it is the first time that oscillatory power changes due to language learning have been studied. Although there are studies showing oscillatory modulations in L1 sentence processing (Lam et al., 2016), the effect of learning on oscillations was not tested yet. However, our experiment was not able to detect oscillatory changes, and based on results from Chapter 5, it was hypothesized that when focusing on short time interval measures, oscillatory changes are easier to identify. However, oscillatory changes measured in Chapter 5 do not reflect language learning.

Therefore, with all its caveats, this thesis opens a door to a new way of studying L2 learning. It shows that ERFs are suitable to measure short-term language related changes, that anatomical correlates of these effects can be successfully measured non-invasively, and that just a few minutes of training are needed to start seeing the first changes related to learning. Regarding oscillations, further work needs to be done in order to assess if they are well suited for studying short-term learning related brain plasticity.

Resumen

El cerebro humano es un órgano que, aunque se está estudiando ampliamente, sigue siendo un misterio. Queda un largo camino hasta entender como su circuitería resulta en acciones tan fascinantes como el lenguaje. Y el misterio del misterio, mientras la mayoría de niños adquieren su lengua materna sin mayor dificultad, los adultos que aprenden un segundo idioma suelen presentar un resultado menos exitoso. ¿Qué procesos cognitivos tienen lugar en el cerebro adulto mientras se aprende un idioma?

Los humanos tenemos la capacidad de adquirir nuevas habilidades, nuevas formas de conducta y adaptarnos a nuevos entornos. El aprendizaje es el proceso de cambio de conducta debido a la experiencia. La plasticidad cerebral es la habilidad de moldear la organización anatómica y funcional del cerebro dependiendo de la demanda y la experiencia (por ejemplo, durante el aprendizaje de un idioma), y a su vez, la plasticidad cerebral permite el desarrollo de capacidades cognitivas (Uylings, 2006). A principios del siglo XX los investigadores creían que no era posible tener cambios anatómicos después de las primeras etapas del desarrollo (Nieto-Sampedro and Nieto-Díaz, 2005). Sin embargo, a finales de los años 50 Liu and Scott (1958) demostraron que la capacidad de modificar la anatomía y la funcionalidad del sistema nervioso se mantiene a lo largo de la vida. El debate de la plasticidad cerebral en la edad adulta se solventó, proponiendo que el desarrollo del cerebro humano está compuesto de diferentes procesos y que cada uno de ellos presenta un perfil de plasticidad diferente (Uylings, 2006).

Análisis con diferentes escalas temporales y espaciales son sensibles a diferentes perfiles de plasticidad que se relacionan con diferentes cambios en la conducta. Por ejemplo, a muy pequeña escala, la plasticidad neuronal evalúa los cambios en las conexiones sinápticas entre neuronas. No obstante, este tipo de plasticidad es muy difícil de relacionar con la adquisición del lenguaje puesto que este proceso ocurre a una escala inaccesible para la mayoría de técnicas de medición en humanos. Al contrario, evaluar la plasticidad a una escala del cerebro se puede medir mediante técnicas no invasivas. Este tipo de plasticidad es más sencilla de relacionar con el

aprendizaje del lenguaje puesto que puede medirse en vivo.

De entre las diferentes técnicas no invasivas, la magnetoencefalografía (MEG) parece ser la más indicada para estudiar la plasticidad cerebral debido al aprendizaje de un nuevo idioma. La MEG mide las fluctuaciones de los potenciales post-sinápticos, que aproximadamente tienen una escala temporal de 5-10 ms (Lopes da Silva, 1991), lo que la hace apropiada para la escala temporal de los procesos relacionados con el lenguaje. Junto con diseños experimentales motivados psicológicamente y lingüísticamente, esta técnica permite estudiar 'cuando' ocurren los diferentes subprocesos: integración acústica-fonológica, el procesado de la sintáctica y la semántica, la integración sintáctico-semántica, etc. (Friederici, 2011). Además, debido a las propiedades físicas de los campos magnéticos, la MEG permite obtener la reconstrucción de las fuentes (Baillet, 2017). Los correlatos anatómicos obtenidos mediante la reconstrucción de fuentes aportan una información muy valiosa para entender mejor los cambios plásticos que ocurren durante el aprendizaje.

Aunque la mayoría de estudios se han centrado en el aprendizaje a largo plazo (Caffarra et al., 2015), estudios recientes también han mostrado interés en el aprendizaje a corto plazo (por ejemplo, Davidson and Indefrey, 2009a). Los estudios de aprendizaje a corto plazo suelen valerse de idiomas miniaturizados que permiten un mejor control de las propiedades a aprender y de la competencia adquirida por los participantes. Estos diseños permiten capturar los cambios cerebrales que tienen lugar durante el aprendizaje. La mayoría de los estudios a corto plazo se han centrado en el aprendizaje de gramática (Mueller et al., 2005, 2007, 2008; Davidson and Indefrey, 2009a,b, 2011), que junto con la fonología es el ámbito del lenguaje que más cuesta adquirir (Uylings, 2006). Los citados estudios encontraron cambios en las señales eléctricas del cerebro tan sólo con unas pocas horas, e incluso minutos, de aprendizaje. Sin embargo, estos estudios recogieron los datos mediante la técnica de electroencefalografía (EEG) y no reportan ningún indicador anatómico de los efectos.

La presente tesis doctoral presenta dos estudios de aprendizaje de lenguaje a corto plazo realizados en la MEG, que reportan correlatos anatómicos de los cambios en la señal magnética recogida. Además se incluye un tercer estudio en la lengua materna de los participantes con el objetivo de entender mejor el rol de las oscilaciones neuronales en el proceso de recuperación de memoria.

6.5 Experimento 1: Aprendizaje de gramática

El primer experimento estudia la adquisición de una nueva norma gramatical, reportando la reconstrucción de fuentes de actividad cerebral evocada recogida con

MEG antes, durante y después del aprendizaje gramatical. El estudio se realizó en dos sesiones de días contiguos. El aprendizaje de gramática se evaluó utilizando una tarea de decisión sobre violación-control. Las proporciones de aciertos y las señales MEG fueron grabadas antes, durante y después de la práctica y se compararon con grabaciones en la L1 de los participantes. Los participantes fueron instruidos en concordancia de número de sintagmas nominales en Euskera, es decir, una regla morfosintáctica. Se utilizó un vocabulario de cognados Castellano-Euskera, para reducir la carga semántica y liberar recursos para el procesado de las violaciones sintácticas (Mueller et al., 2008). La tarea que se realizó después de la práctica es una tarea de generalización que consistía en una tarea de decisión en la misma norma morfosintáctica pero aplicada a un nuevo vocabulario (también cognado). La hipótesis del estudio fue que al usar un vocabulario cognado, las normas gramaticales podrían ser incorporadas rápidamente. Antes de la práctica los participantes no eran capaces de juzgar debidamente los sintagmas nominales. No obstante, en el primer bloque de práctica, justo después de la explicación de la norma, los participantes fueron altamente precisos en su decisión. Fueron capaces de mantener esta precisión durante todos los bloques de práctica y también en el bloque de generalización. Esto sugiere que la rápida adquisición de la gramática es posible en adultos, por lo menos cuando la práctica es intensiva y concentrada.

Por otro lado, la red involucrada en el procesado de las violaciones gramaticales cambió con la práctica. Durante el primer bloque de práctica, el efecto de gramaticalidad fue localizado en los lóbulos temporal derecho y fronto-parietal derecho. Estas áreas se han relacionado previamente con la detección de errores (Indefrey et al., 2001). Además, en base al modelo HERA (hemispheric encoding/retrieval asymmetry) la corteza prefrontal derecho está relacionado con la recuperación de memoria (Habib et al., 2003). Sin embargo, en el siguiente bloque de práctica, el efecto de gramaticalidad se localizó en los lóbulos parieto-temporal izquierdos. Por último, en el tercer bloque de práctica y en el test de generalización, el efecto se observa en el lóbulos temporal izquierdo. Estos cambios se pueden interpretar como un proceso de 'gramaticalización de la norma' en el que los participantes necesitan tiempo antes de transferir el conocimiento de una norma a su sistema de procesado en tiempo real (McLaughlin et al., 2010).

6.6 Experimento 2: Comprensión de frases

El experimento 2, utiliza una tarea de escucha de frases para examinar el aprendizaje de un idioma. En este caso, los participantes (ingleses) escucharon frases tanto en el idioma materno como en un idioma no conocido (Castellano) mientras

las señales MEG eran grabadas. Después, fuera de la MEG, fueron instruidos en el vocabulario necesario para entender las frases en el nuevo idioma. Además de aprender el vocabulario, practicaron la escucha de frases completas creadas con el nuevo vocabulario. Al día siguiente, los participantes volvieron a escuchar frases en el idioma materno y en el idioma recién aprendido mientras las señales MEG eran grabadas y se realizaron tests de comprensión después de cada sesión de MEG. En el test del día uno, los participantes sólo fueron capaces de reconocer algunas pocas palabras y no eran capaces de comprender frases completas. Sin embargo, en el test del segundo día las respuestas de los participantes en el test de comprensión fueron muy precisas. Esto sugiere no solo que el aprendizaje de vocabulario puede ser rápido, sino que el vocabulario adquirido puede ser segmentado e identificado dentro del habla, y que los significados de las diferentes palabras puede combinarse para entender las frases tan solo después de una sesión de práctica.

En este experimento se analizó la actividad oscilatoria en respuesta a la escucha de frases. Para ello se midieron los cambios de la potencia entre el tiempo de silencio y escucha de frases para cada una de las bandas de frecuencia. Los cambios de potencia se localizaron en la red del lenguaje tanto al escuchar el idioma materno como al escuchar el nuevo idioma, aunque los cambios de potencia eran mayores para el nuevo idioma. Estos resultados sugieren que idiomas no conocidos requieren un mayor procesamiento de información en las áreas relacionadas con el lenguaje y una mayor inhibición en las áreas no relacionadas con la tarea. No se encontraron evidencias sólidas de cambios de potencia debido al aprendizaje de vocabulario en el nuevo idioma. Estos resultados sugieren que la respuesta oscilatoria en el periodo de una frase capta los diferentes procesos que ocurren durante la escucha de una frase, y que los pequeños cambios que pudieran ocurrir en alguno de esos procesos quedan difuminados.

6.7 Experimento 3: Recuperación de la memoria en L1

En el experimento 3, la recuperación de memoria en la L1 se estudió mediante material auditivo. Los participantes tenían que memorizar listas de 50 palabras por lista. Para cada lista, las palabras aparecían en solitario en la pantalla. Seguidamente, los participantes realizaron 5 min de práctica durante los cuales tenían que repasar la lista mentalmente. Finalmente se realizó una tarea de reconocimiento con materiales auditivos. La práctica y la tarea de reconocimiento se realizaron en dos condiciones diferentes, con los ojos abiertos y los ojos cerrados. Se hipotetizó que los participantes reconocerían un mayor número de palabras con los ojos cerrados. No obstante, los resultados demostraron que cerrar los ojos no moduló la conducta

de los participantes.

En cuanto a las señales MEG, el estado con los ojos cerrados provocó un esperado incremento en la banda alfa de frecuencia (8-13 Hz) en los sensores parieto-occipitales. No obstante, las modulaciones de alfa debido a palabras recordadas u olvidadas se encontraron en los sensores temporales, lo cual nos permite inferir que estas oscilaciones se deben al llamado ritmo tau, en lugar de alfa. Además, no se encontró ninguna interacción entre los ritmos alfa y tau. Estos resultados sugieren que en tareas de memoria auditiva los efectos en tau están relacionados con el rendimiento de la memoria, y que estos efectos en el ritmo tau se pueden medir con MEG, al contrario que en EEG. Estos resultados también sugieren que el rol de los ritmos alfa y tau son diferentes aunque ambos oscilen en un rango de frecuencias similar. Por ello, a la hora de interpretar los resultados de análisis oscilatorios, no sólo hay que tener en cuenta la frecuencia si no también la topografía de los efectos.

6.8 Discusión general

Los resultados del experimento 1 son congruentes con otros resultados de aprendizaje a corto plazo (Mueller et al., 2008, 2007, 2005; Davidson, 2010; Davidson and Indefrey, 2009a), demostrando que la funcionalidad de las redes neuronales puede cambiar con unas pocas horas (o incluso minutos) de práctica asemejándose a las redes que se activan durante un procesamiento en L1. Sin embargo, a primera vista, estos resultados son incongruentes con los estudios de aprendizaje a largo plazo. Estudios longitudinales han demostrado que en alumnos de primer año de cursos oficiales de idiomas, el efecto de gramaticalidad en L2 muestra patrones diferentes a los patrones nativos (McLaughlin et al., 2010). Una posibilidad es que, mientras en los estudios de aprendizaje a corto plazo los participantes practican y son evaluados en pequeños fragmentos de un idioma, los participantes de estudios longitudinales adquieren una variedad de rasgos del idioma, pero únicamente son evaluados en un pequeño fragmento. Puede ser que el fragmento en el que son testeados todavía no esté del todo 'gramaticalizado' (McLaughlin et al., 2010). Otra posibilidad es que ocurran cambios rápidos durante el aprendizaje intensivo pero que estos no resulten en cambios cerebrales a largo plazo a menos que la práctica se mantenga en el tiempo.

En el experimento 2, no se encontraron evidencias claras de modulación de la actividad oscilatoria debido al aprendizaje. Uno de los motivos puede ser que, como la escucha de frases depende de varias funciones cognitivas (segmentación,

reconocimiento de palabras, integración de todos los significados, etc.), una sola sesión de práctica no sea suficiente para provocar cambios en la actividad oscilatoria. Otra posibilidad es que se hayan producido cambios, pero estos no hayan podido ser detectados. El análisis realizado en los datos recogidos muestran la actividad oscilatoria asociada varias funciones cognitivas diferentes que ocurren durante la escucha de una frase. Puede ser que si el análisis se enfocase en periodos de oscilación más cortos, los cambios en la actividad oscilatoria fuesen visibles, como en el experimento 3.

Una pregunta recurrente en el ámbito de la investigación de la adquisición de una segunda lengua es si la red del lenguaje está involucrada desde el principio del aprendizaje o si por el contrario se reclutan áreas del cerebro encargadas de otras funciones cognitivas (Indefrey, 2006). Aunque el experimento 1 carece de una comparación estadística de las respuestas en la L1 y la L2, se ofrece una comparación cualitativa. Desde el segundo bloque de práctica, el patrón del efecto de gramaticalidad se localiza en el lóbulos temporal izquierdo y en el giro frontal inferior izquierdo, siendo las dos áreas parte de la red de lenguaje descrita por varios modelos (Hagoort, 2016; Friederici, 2011). Sin embargo, los análisis estadísticos sitúan el efecto en diferentes subregiones de este patrón y van cambiando de bloque en bloque. Este solapamiento parcial en las redes es congruente con un estudio longitudinal realizado con MEG que reportó que las regiones que estadísticamente soportaban el efecto de la gramaticalidad cambiaban de localización dentro del lóbulo temporal entre sesión y sesión (Davidson and Indefrey, 2009b).

Por otro lado, en el experimento 2 se hace una comparación estadística de la actividad oscilatoria en L1 y L2 a escala de cerebro entero. Los resultados de este análisis sugieren que las repuestas oscilatorias en la L2 son más amplias que en la L1. Para la L2 se encontró una mayor desincronización de la frecuencia alfa en los lóbulos temporales y una mayor sincronización en las áreas no relacionadas con la tarea. Una mayor desincronización de la frecuencia alfa se ha relacionado con una mayor capacidad de procesamiento de información (Klimesch et al., 2007; Hanslmayr et al., 2012). Esto sugeriría que los patrones del experimento 2 indican que las áreas temporales requieren mayor procesamiento de información durante la escucha de la L2, mientras que las áreas no involucradas en la tarea requieren mayor inhibición. Estos resultados son congruentes con Indefrey (2006), quien sugiere que durante las fases iniciales del aprendizaje las personas necesitan mayor esfuerzo para completar una tarea y que esto se refleja en áreas del cerebro que son reclutadas más intensamente que en la L1. No obstante, cuando cierto nivel de lenguaje es adquirido, las tareas se realizan más sencillamente y, por lo tanto, los patrones de actividad cerebral se parecen más a los patrones en la L1.

En resumen, esta tesis abre una puerta a una nueva manera de estudiar el aprendizaje del lenguaje en adultos. Los resultados de esta tesis sugieren que la red del lenguaje está presente desde el principio del aprendizaje de la L2, aunque responde de manera diferente que en la L1. Además, el experimento 1 indica que tan solo unos minutos de práctica son necesarios para ver cambios en las redes que respaldan el aprendizaje del lenguaje. Muestra que los campos magnéticos evocados son un buen indicador para el aprendizaje a corto plazo, y que correlatos anatómicos de estos efectos se pueden medir de manera no invasiva. El experimento 2 nos enseña que para otros aspectos del lenguaje, más sesiones práctica son necesarias para detectar los cambios, aunque tampoco se puede descartar la posibilidad de que con un análisis concentrado en un periodo temporal más concreto, se puedan detectar cambios en la actividad oscilatoria.

List of publications derived from the thesis

Bastarrika A. and Davidson D.J. (2017). An Event Related Field Study of Rapid Grammatical Plasticity in Adult Second-Language Learners. *Frontiers in Human Neuroscience*, 11(January):119. doi: 10.3389/fnhum.2017.00012

Bastarrika A., Caballero C., Davidson D.J. (In preparation). Is eye-closure alpha related to memory-promoting alpha?

Bastarrika A. and Gascoyne L., Davidson D.J., Caballero C., Brookes M. (In preparation). The role of cortical oscillations in speech processing at initial stages of second language learning in adults

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