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Language control in bimodal bilinguals: Evidence from ERPs☆

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ABSTRACT

It is currently unclear to what degree language control, which minimizes non-target language interference and increases the probability of selecting target-language words, is similar for sign-speech (bimodal) bilinguals and spoken language (unimodal) bilinguals. To further investigate the nature of language control processes in bimodal bilinguals, we conducted the first event-related potential (ERP) language switching study with hearing American Sign Language (ASL)-English bilinguals. The results showed a pattern that has not been observed in any unimodal language switching study: a switch-related positivity over anterior sites and a switch-related negativity over posterior sites during ASL production in both early and late time windows. No such pattern was found during English production. We interpret these results as evidence that bimodal bilinguals uniquely engage language control at the level of output modalities.

Language selection is a principal challenge for the bilingual mind, as both languages are typically activated in parallel (e.g., Costa et al., 2000; Giezen and Emmorey, 2016; Meade et al., 2018; Thierry and Wu, 2007), and thus compete with one another, either directly or indirectly (e.g., Roelofs et al., 2016). The process that alleviates this competition during unimodal (i.e., two spoken languages) and bimodal (i.e., a signed language and a spoken language) bilingual language production is called language control. While it might seem parsimonious for unimodal and bimodal bilinguals to implement a qualitatively similar language control process, with the possibility of quantitative differences, not all studies provide evidence along these lines (for a discussion, see Emmorey et al., 2016). To further investigate the possibility of similar language control processes between bimodal and unimodal bilinguals, we conducted the first ERP study to examine bimodal language control with the language switching paradigm. Evidence for a similar language control process among these bilingual groups would be found if a comparable ERP pattern would occur during bimodal language switching as during unimodal language switching (e.g., Declerck et al., 2021; Jackson et al., 2001; Kang et al., 2020; Peeters, 2020).

1. Bimodal language control and its relation to unimodal language control

Both bimodal and unimodal language control are typically explained with inhibition on the non-target language (however, see Blanco-Elorrieta and Caramazza, 2021; Costa et al., 1999; Roelofs, 1998). The most prominent model regarding language control, namely the Inhibitory Control Model (ICM; Green, 1998), also relies on inhibitory mechanisms. According to this model, inhibition occurs at two different stages: once between task schemas (i.e., mental "programs" to achieve a goal, such as speaking in a specific language) and between lemmas.

This model and others (e.g., Declerck et al., 2015; Schwieter and Sunderman, 2008) are typically put to the test with the language switching paradigm (for a review, see Declerck and Philipp, 2015) both when testing unimodal bilinguals (e.g., Costa and Santesteban, 2004; Declerck et al., 2012; Meuter and Allport, 1999; Timmer et al., 2019; Verhoef et al., 2009; for a review, see Declerck and Philipp, 2015) and bimodal bilinguals (Blanco-Elorrieta et al., 2018; Dias et al., 2017; Emmorey et al., 2020; Kaufmann et al., 2018; Kaufmann and Philipp,

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2017; Lu et al., 2019; however, see Emmorey et al., 2021; Giezen et al., 2015). Language switching generally involves bilinguals naming a visual stimulus (e.g., a digit or a picture) in one of two languages as determined by a cue (e.g., colored squares). Since both languages are used within a block, trials are preceded either by trials in the same language (repetition trials) or the other language (switch trials). Performance during switch trials is typically worse than during repetition trials. This performance difference is called the "switch cost" and serves as a measure of language control (e.g., Declerck and Philipp, 2015; Green, 1998).

While the vast majority of language switching studies have been conducted with unimodal bilinguals, a similar performance decrease when switching between spoken and signed languages has been observed in several studies (Dias et al., 2017; Kaufmann et al., 2018; Kaufmann and Philipp, 2017; see also Emmorey et al., 2020), which provides evidence for language control during bimodal language production. For instance, Dias et al. (2017) asked bimodal bilinguals to switch between Spanish and Spanish Sign Language (LSE), which resulted in switch costs. Additionally, their results showed asymmetrical switch costs, i.e., larger switch costs for the dominant language (Spanish) than the non-dominant language (LSE), which parallels the pattern observed in unimodal bilingual studies (e.g., Ma et al., 2016; Macizo et al., 2012; Meuter and Allport, 1999). This asymmetrical pattern is typically taken as evidence for inhibitory control on the non-target language (e.g., Green, 1998; Meuter and Allport, 1999).[1] Based on these findings, Dias and colleagues suggested that the underlying mechanism of language control is to a large degree similar across bimodal and unimodal language production.

Yet not all results point to similar control processes during bimodal and unimodal language production. For example, Kaufmann et al. (2018) tested German participants who were familiar with German, German Sign Language (DGS), and English. Their results showed smaller German switch costs when switching between German and DGS than when switching between German and English. The authors explained this bimodal switch advantage in terms of different control processes during bimodal and unimodal language processing. More specifically, the bimodal switch advantage was mainly attributed to control processes being implemented at the output level for bimodal bilinguals and at the lemma level for unimodal bilinguals, with the latter interference being more difficult to resolve. However, Kaufman and colleagues also pointed out that their results could, partially, be due to a difference in language proficiency, as these participants were more proficient in English than in DGS. Consequently, there would be less confusability between German and DGS than between German and English, which could have led to smaller German switch costs when paired with DGS. Another alternative is that there is less competition at the lexical or phonological level during bimodal than unimodal language production, which would result in less of a need for language control in a bimodal context. So, while this study indicates that there is some difference between bimodal and unimodal language control, the exact difference is not entirely clear.

In the current study, we set out to investigate bimodal language control measuring ERPs to examine the neurocognitive mechanisms related to bimodal language control. Most unimodal language control studies that have included ERPs have focused on stimulus-locked activity (e.g., Christoffels et al., 2007; Jackson et al., 2001; Kang et al., 2020; Martin et al., 2013; Peeters and Dijkstra, 2018; Verhoef et al., 2009). Several of these studies have found evidence that the N2 ERP component is sensitive to language switching (e.g., Jackson et al., 2001; Kang et al., 2020) such that it is generally, but not always, larger in switch than repetition trials (see Table 1 for a literature overview of production-based unimodal language switching studies). The N2 effect is strongest over anterior sites around 200–350 ms after stimulus onset and is typically associated with inhibitory control or conflict monitoring. Some of the language switching studies that observed a switch-related N2 effect have also found that it was modulated by language dominance, with a larger switch-related N2 effect in the less dominant language (e.g., Jackson et al., 2001; Zheng et al., 2020). This is typically explained by assuming that trials in the less dominant language require more inhibition of the dominant language than vice versa because the dominant language is used more often and should therefore have a larger base activation.

After the N2, two distinct ERP patterns have been observed during unimodal language switching. Several language switching studies found a late positive complex (LPC; Jackson et al., 2001; Liu et al., 2016; Martin et al., 2013), which is seen as an index of stimulus-response mapping reconfiguration during language switching. This pattern reflects a larger positivity for switch than repetition trials around 400–650 ms, especially over posterior sites. Other studies have observed a switch-related negativity (e.g., Declerck et al., 2021; Kang et al., 2020; Peeters, 2020; Peeters and Dijkstra, 2018), which has been interpreted as reflecting the increased difficulty in retrieving word meaning when switching languages. This pattern is characterized by a larger negativity for switch than repetition trials. There is quite some variability regarding the onset of this pattern, and it typically lasts until the end of the epoch.

To investigate bimodal language control, we used a similar methodology as in the unimodal language switching study of Declerck et al. (2021), as this would allow us to draw firmer conclusions about any commonalities and/or differences between unimodal and bimodal bilinguals. In that study, we tested unimodal language control by asking English-Spanish bilinguals to name either the semantic category of a picture or the color in which it was presented in a language switching paradigm. The same tasks were used in the current experiment but with hearing bimodal bilinguals who were proficient in English and American Sign Language (ASL). Our main focus, similar to previous ERP unimodal language switching studies, will be on ERPs time-locked to picture onset in language-switch trials relative to language-repetition trials.

If bimodal language control is similar to unimodal language control, then the unimodal language switching ERP literature lends itself to clear predictions. In that case, we would expect a larger N2 in switch trials relative to repetition trials (e.g., Jackson et al., 2001; Kang et al., 2020). Moreover, we would expect a larger LPC (post-N2) for switch than repetition trials (Jackson et al., 2001; Liu et al., 2016; Martin et al., 2013) or a switch-related negativity (Declerck et al., 2021; Kang et al., 2020; Peeters, 2020; Peeters and Dijkstra, 2018). Yet, based on some behavioral bimodal language switching studies (e.g., Kaufmann et al., 2018), we might expect a different switch-related ERP pattern for bimodal than unimodal bilinguals. Since no ERP research has been conducted into bimodal language switching before, it was unclear how this difference would manifest itself in the ERP data.

2. Method

2.1. Participants

Twenty-two hearing ASL-English bilinguals took part in the experiment. Two participants were excluded due to experimenter error. The remaining 20 participants were on average 26.0 years old (SD = 6.8 years) and consisted of 17 women. All but two participants were right handed and no one had a prior history of neurological dysfunctions. Five of the bimodal bilinguals were Codas (bimodal bilinguals who were

[1] Based on the ICM (Green, 1998) and Meuter and Allport (1999), asymmetrical switch costs are generally accounted for by a larger L1 than L2 base activation, because L1 is used more in daily life. This should result in more inhibition being required to resolve L1 interference during L2 production than vice versa. In turn, more inhibition will persist into the following trial, and thus will be more difficult to overcome, when switching languages.

Table 1

Summary of ERP production-based unimodal language switching studies, with a focus on number of participants included in the main analysis (N), which language combinations were used, the examined time window(s), the direction of the difference between switch and repetition trials, the Anterior/Posterior distribution of this effect, and which reference was used for the ERP analyses.

Study	N	Language combination(s)	Time window(s)	Direction	Anterior/Posterior	Reference
Christoffels et al. (2007)	20	German-Dutch	275–375 ms 375–475 ms	Larger negativity for L1 repetition trials Larger negativity for L1 repetition trials	No specific distribution Anterior	Average mastoid reference
Declerck et al. (2021)	24	English-Spanish	200–350 ms 400–600 ms	Larger negativity for switch trials Larger negativity for switch trials	No specific distribution No specific distribution	Left mastoid reference
Jackson et al. (2001)	20	English-French/German/Spanish/Manderin/Urdu	300–350 ms (time course analysis) 385–700 ms (time course analysis)	Larger negativity for L2 switch trials Larger positivity for switch trials	Only frontal and central electrodes were examined Only parietal electrodes were examined	Global average reference
Kang et al. (2020)	52	Chinese-English	210–250 ms 250–370 ms 410–510 ms	Larger negativity for switch trials Larger negativity for switch trials Larger negativity for switch trials	Only frontal and central electrodes were examined	Average mastoid reference
Martin et al. (2013)	36	Spanish-Catalan-English	250–350 ms 500–650 ms	No significant difference Larger positivity for switch trials in the non-dominant language	Only frontal electrodes were examined Only parietal electrodes were examined	Global average reference
Massa et al. (2020)	32	French-Italian	250–350 ms	No significant difference	N/A	Average mastoid reference
Peeters (2020)	23	Dutch-English	452–700 ms (cluster-based permutation)	Larger negativity for switch trials	N/A	Average mastoid reference
Peeters and Dijkstra (2018)	23	Dutch-English	540–700 ms (cluster-based permutation)	Larger negativity for switch trials	No specific distribution	Average mastoid reference
Verhoef et al. (2009)	17	Dutch-English	300–360 ms	No significant difference	N/A	Average mastoid reference
Zheng et al. (2020)	25	Dutch-English	200–350 ms	Larger negativity for L2 switch trials	Posterior	Average mastoid reference

Note: Studies that included manipulations that would alter the overall language switching context (e.g., transcranial magnetic stimulation or training) were not included. We did not include any time windows prior to 200 ms after picture onset since the current study focuses on the N2 and post-N2 components.

Table 2
Means for the demographic information (SD in parentheses) for each language.

	English	ASL
Age of acquisition (years)	1.4 (2.6)	15.5 (11.2)
Time currently used (%)	76.8 (18.8)	21.6 (18.8)
Time used during childhood (%)	81.6 (24.6)	12.6 (24.6)
Production[a]	6.9 (0.6)	5.0 (1.2)

[a] Self-rated scores on a scale of 1 (low proficiency) to 7 (high proficiency).

exposed to sign language from birth).[2] The other demographic and language information can be found in Table 2. All participants were volunteers who were paid for their time. Informed consent was obtained in accordance with the local Institutional Review Board.

2.2. Stimuli

Forty-eight line drawings were used, each of which was presented in one of four colors (brown, green, blue, and orange). An equal number of pictures was presented in each of the colors. Each picture depicted a concept from one of four semantic categories (furniture, clothing, food, and animals). An equal number of pictures was part of each category.

Participants were instructed to produce either English or ASL based on one of two shape cues which subtended a maximal visual angle of 2.7° in each direction. Any given participant saw either a square and a circle or a pentagon and a parallelogram as cues in the language switching paradigm. The remaining two cues were used for a separate task switching paradigm that occurred within the same recording session, either before or after the language switching paradigm. Here, we focus solely on the language switching performance (see Supplementary Materials for the task switching results). Additional analyses showed that paradigm order (language vs. task switching first) did not have a reliable influence on the significant, observed effects ($.118 < ps < .569$).

2.3. Procedure

Each of the two language switching blocks was comprised of 96 trials, and each was preceded by a practice block of 20 trials. Participants had to respond in English or ASL, depending on the cue. In one block, they named the semantic category of the picture, whereas in the other block they named the color in which the picture was presented.

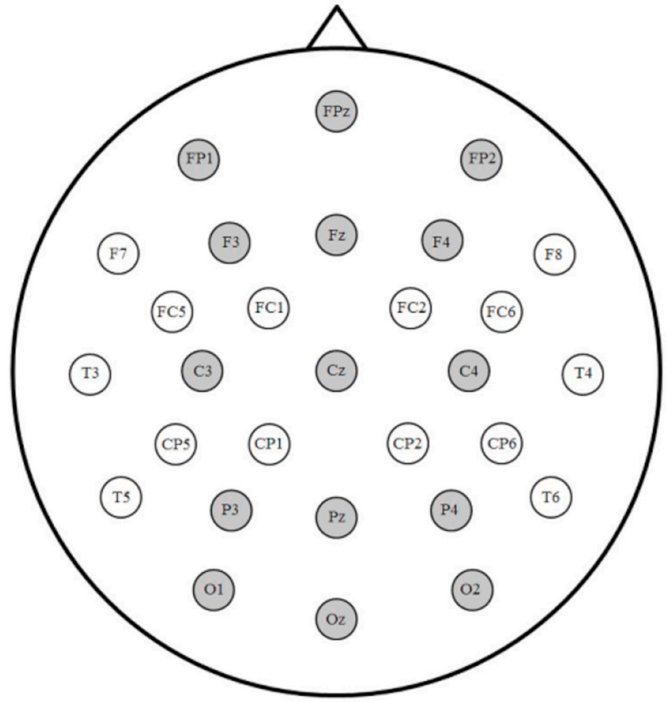

Fig. 2. Sites highlighted in grey were included in the analyses.

The order of these two blocks was counterbalanced across participants.

In keeping with most studies that require sign language production, participants were asked to press a spacebar with both hands and only release the spacebar to respond (either vocally or manually). Trials started with a central fixation cross for 500 ms, followed by a blank screen for 300 ms. This was succeeded by the presentation of the cue shape for 800 ms, after which the picture was presented in the middle of the shape cue for 1000 ms. Then a blank screen was presented for 1700 ms plus a jitter between 0 and 400 ms. The next trial was initiated when the space bar was pressed after responding. For a visual depiction of the trial procedure, see Fig. 1. Participants were also asked to blink mainly after responding and prior to the fixation cross of the next trial.

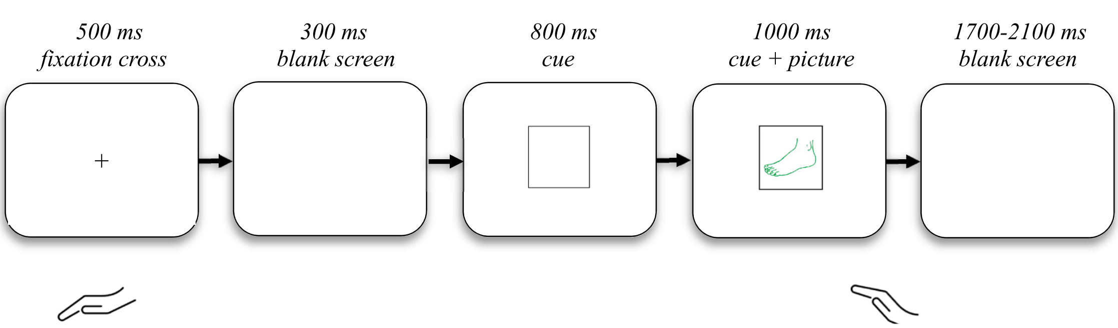

Fig. 1. Overview of the trial procedure. The hands underneath the trial procedure indicate that the participants pushed down on the space bar to initiate a trial. They released the space bar just before responding.

2.4. Behavioral analyses

The independent variables in the behavioral analyses were Language (English vs. ASL) and Trial type (switch vs. repetition trials). Reaction time (RT) and error rate were the dependent variables. For the vocal responses, the RTs were measured from picture onset until speech onset. For the ASL responses, the RTs were measured from picture onset until

[2] Previous language switching studies have not found a connection between age-of-acquisition and language-switch costs (Bonfieni et al., 2019; Costa et al., 2006). Hence, we do not think that the inclusion of non-Codas substantially influenced our results. In addition, most studies with hearing bimodal bilinguals include a mix of Codas and proficient non-Codas.

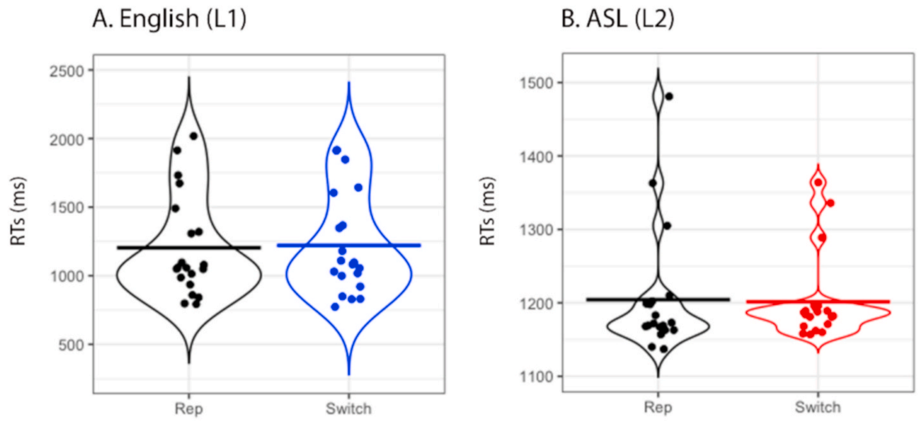

Fig. 3. Violin plots of English (A) and ASL (B) RTs as a function of Trial type (switch vs. repetition). Please note that different y-axis scales are used for English and ASL to better depict the distribution for each language.

the space bar was released.

Regarding the error analysis, we excluded errors that were preceded by omissions or by other errors, since it is not clear whether these trials should be considered language switch or repetition trials (0.3% of the overall data). Responses were considered errors if they were incorrect with regard to the target language or the target word/sign, as noted by a trained research assistant proficient in both English and ASL.

Regarding the RT analysis, we excluded all trials with 2.5 standard deviations above or below the RT mean of each language per participant (cf. Emmorey et al., 2020). In addition, the first trial of each block, error trials, and trials following error trials or an omission (see rationale above) were excluded. Based on these criteria, 5.13% of trials were excluded from the RT analysis.

2.5. EEG recording and analyses

Electro-Caps with 29 active electrodes were used on all participants. Four more electrodes were used: one under the left eye to identify blinks (relative to FP1 activity), one next to the outer canthus of the right eye to identify horizontal eye movements, and one on each mastoid. The signal from the left mastoid was used as a reference during recording and for the ERP analyses. The signal of the right mastoid was used to assess any possible differences in mastoid activity (no differences between conditions were observed at the right mastoid). Impedances were maintained below 2.5 kΩ. EEG was amplified using SynAmps RT amplifiers (Neuroscan-Compumedics) with a bandpass of DC to 100 Hz and was sampled throughout at 500 Hz.

The epoch was time-locked to picture onset and was 700 ms long, which included a baseline of 100 ms prior to the picture onset. The duration of the ERP epoch was based on the shortest RTs in order to minimize any production-related artifacts. Detected artifacts, such as blinks or other eye movements, led to the exclusion of the corresponding trial from the analyses. The following trials were also excluded from analyses: the first trial of each block, error trials, and trials immediately following these errors. This procedure led to the exclusion of 10.34% of trials. The analyses included an average of 42.70 (SD = 4.03) English switch trials, 43.00 (SD = 3.32) English repetition trials, 43.05 (SD = 3.46) ASL switch trials, and 43.40 (SD = 3.69) ASL repetition trials per participant. No significant differences were observed in the average number of trials per participant between any two conditions (.175 < *ps* < .919).

ERPs were averaged per condition and participant at each electrode and low-pass filtered at 15 Hz. Mean N2 amplitudes were calculated per subject between 200 and 350 ms (cf. Declerck et al., 2021). We were also interested to see whether a switch-related negativity or LPC would be observed in the late time window (i.e., 400–600 ms; cf. Declerck et al., 2021). As depicted in Fig. 2, we used a broad grid of 15 electrodes (cf. Declerck et al., 2021). The omnibus ANOVA consisted of Language (English vs. ASL), Trial type (switch vs. repetition trials), Anterior/Posterior (prefrontal, frontal, central, parietal, occipital), and Laterality (left, midline, right). Greenhouse-Geisser correction was applied on all measures that have a numerator with more than one degree of freedom.

Table 3
Overall percentage of errors (SD in parentheses) as a function of Language (English vs. ASL) and Trial type (switch vs. repetition).

	Error rate
English switch	1.79 (1.96)
English repetition	0.84 (1.42)
English switch costs	*0.95*
ASL switch	1.16 (1.45)
ASL repetition	1.15 (1.72)
ASL switch costs	*0.01*

3. Results

3.1. Behavioral results

The reaction time analysis (see Fig. 3 for mean reaction times per condition) and the error rate analysis (see Table 3 for mean error rates per condition) showed no significant effects.[3]

Based on the violin plots (Fig. 3), we examined whether any participants had substantially longer response times relative to the overall average across participants. One participant had an overall average ASL RT above 2.5 SD of the overall average ASL RT across participants. Additional analyses without this participant still showed no significant effects in the reaction time analysis nor the error rate analysis. We also checked if any participants had substantially more errors than the overall average per language (i.e., >2.5 SD above the overall mean across participants). However, this was not the case for either English or ASL.

3.2. ERP results

Early time window (200–350 ms). In the early time window, a significant interaction was observed between Trial type and Anterior/Posterior, $F(4, 76) = 7.76$, $p = .003$, $\eta_p^2 = .290$, indicating a larger negativity in switch compared to repetition trials, especially over

[3] The data are available on https://osf.io/gh347.

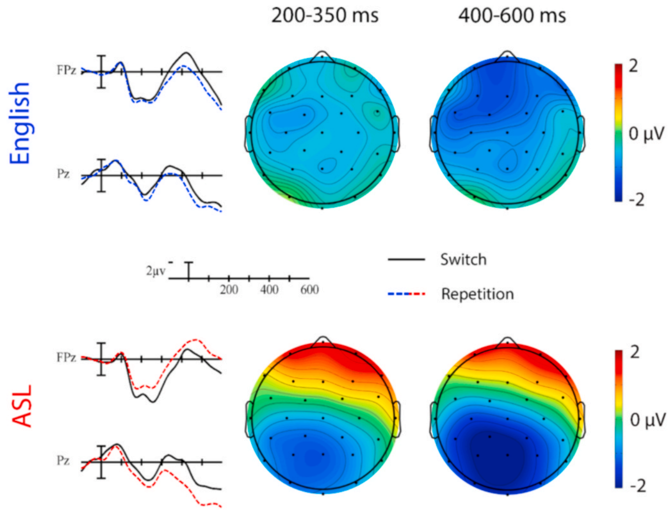

Fig. 4. On the left side of this figure are the grand average picture-locked ERP waveforms at representative electrodes FPz and Pz elicited by switch trials (solid line) and repetition trials (dotted line) during English (upper two waveforms in blue) and ASL (lower two waveforms in red). Each vertical tick marks 100 ms and negative is plotted up. The calibration bar marks 2 μV. On the right side of the figure are the scalp voltage maps that show the distribution of the picture-locked Trial type effect (switch trials – repetition trials) in the 200–350 ms (left voltage map) and 400–600 ms (right voltage map) time windows for English and ASL. Cool colors indicate a larger negativity for switch trials relative to repetition trials. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

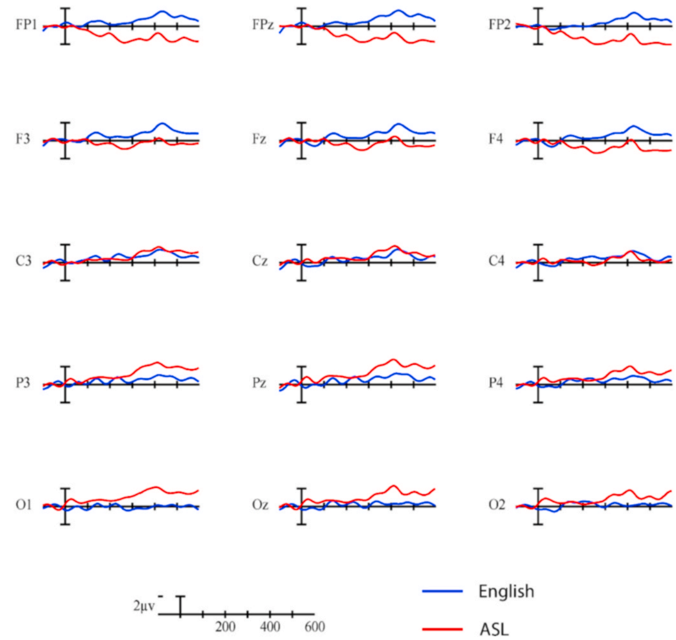

Fig. 5. Differences waves based on subtracting the ERPs of repetition trials from switch trials for English (blue) and ASL (red). Each vertical tick marks 100 ms and negative is plotted up. The calibration bar marks 2 μV. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

posterior sites. There was also a significant three-way interaction between Language, Trial type, and Anterior/Posterior, $F(4, 76) = 6.86$, $p = .004$, $\eta_p^2 = .265$ (see Figs. 4 and 5). Separate analyses for each language demonstrated that during ASL trials there was a larger positivity in switch compared to repetition trials over anterior sites and the opposite pattern over posterior sites, $F(4, 76) = 14.50$, $p < .001$, $\eta_p^2 = .433$. In contrast, no effects or interactions including Trial type reached significance for English trials ($.286 < ps < .743$).

We also performed an additional analysis without the participant that had an average RT in ASL more than 2.5 SD longer than the average ASL RT across participants, which resulted in the same pattern of significance as the analysis above.

Late time window (400–600 ms). In the late time window, a significant interaction was observed between Trial type and Laterality, $F(2, 38) = 5.91$, $p = .010$, $\eta_p^2 = .237$, indicating a larger negativity in switch trials compared to repetition trials, especially over left hemisphere sites. The interaction between Trial type and Anterior/Posterior was also significant, $F(4, 76) = 7.04$, $p = .004$, $\eta_p^2 = .270$, indicating a larger negativity in switch trials compared to repetition trials, especially over posterior sites. There was also a significant interaction between Language and Anterior/Posterior, $F(4, 76) = 7.05$, $p = .005$, $\eta_p^2 = .271$, indicating a larger negativity during ASL than English trials, especially over anterior sites. The analysis also showed a significant three-way interaction between Language, Laterality, and Anterior/Posterior, $F(8, 152) = 5.67$, $p = .001$, $\eta_p^2 = .230$, indicating a larger negativity during ASL than during English trials, especially over anterior sites on the left hemisphere. Finally, there was a significant three-way interaction between Language, Trial type, and Anterior/Posterior, $F(4, 76) = 10.99$, $p < .001$, $\eta_p^2 = .367$ (see Figs. 4 and 5). Separate analyses for each language showed that during ASL trials there was a larger positivity elicited by switch compared to repetition trials over anterior sites and the opposite pattern over posterior sites, $F(4, 76) = 19.50$, $p < .001$, $\eta_p^2 = .507$. In contrast, no effects or interactions including Trial type reached significance for English trials ($.091 < ps < .715$).

We also performed an additional analysis without the participant that had an average RT in ASL more than 2.5 SD slower than the average ASL RT across participants. This resulted in the same pattern of significance as the analysis above apart from one effect. The main effect of Trial type became significant, $F(1, 18) = 4.90$, $p = .040$, $\eta_p^2 = .214$, indicating a larger negativity in switch trials compared to repetition trials.

4. Discussion

In the current ERP study, we focused on the neurocognitive mechanisms underlying bimodal language control by examining language switching between ASL and English. Even though no behavioral switch costs were observed, switch trials elicited a larger positivity than repetition trials over anterior sites and a larger negativity over posterior sites in both the early (200–350 ms) and late (400–600 ms) time windows during ASL production. During English production, on the other hand, no such pattern was observed.

Before delving into the ERP results, we first want to address the behavioral results. The absence of language-switch costs with bimodal bilinguals could in part be due to the advantage of switching between a sign language and a spoken language that was observed by Kaufmann et al. (2018). Yet, this study still showed bimodal language-switch costs, as have bimodal language switching studies that solely focused on language-switch costs without the comparison to unimodal language switching (Dias et al., 2017; Kaufmann and Philipp, 2017; see also Emmorey et al., 2020). We believe that several characteristics of our methodology could be responsible for the absence of behavioral language-switch costs in the current study. For instance, to minimize language production artifacts in the electrophysiological signal, the current study had much longer intervals between the time that the participants responded and the next stimulus (response-to-stimulus interval) and between the presentation of the cue and the presentation of the stimulus (cue-to-stimulus interval). Ma et al. (2016) found that increasing the response-to-stimulus interval leads to substantially smaller switch costs. A longer cue-to-stimulus interval is also known to decrease switch costs (e.g., Costa and Santesteban, 2004; Declerck et al., 2020; Ma et al., 2016). The culmination of these factors, together with the bimodal switch advantage (Kaufmann et al., 2018), could have increased the probability of null behavioral switch costs in the current study.

The fact that we only observed differences between switch and repetition trials in the ERPs, but not the behavioral data, is not uncommon in the ERP literature (for a discussion, see Meade et al., 2019). ERPs measure how various neural processes unfold over time and can reflect transitory differences that do not ultimately have a substantial influence on behavior.

Regarding the ERPs, recall that several previous unimodal language switching studies observed a switch-related N2 pattern early on (see Table 1; e.g., Jackson et al., 2001). After the switch-related N2, unimodal language switching studies observed either a switch-related LPC (e.g., Liu et al., 2016; Martin et al., 2013) or a post-N2 negativity (e.g., Declerck et al., 2021; Peeters, 2020). We reasoned that if bimodal and unimodal language control are similar, then a similar ERP pattern would be expected during bilingual language switching irrespective of modality. However, this does not seem to be the case. In the early time window, we observed a larger positivity during switch than repetition trials over anterior sites and the opposite pattern over posterior sites, but only for ASL. This is not in line with the typical N2 pattern observed in unimodal language switching, which is generally characterized by a larger *negativity* during switch than repetition trials over anterior sites (e.g., Jackson et al., 2001; Kang et al., 2020). In the late time window, we observed a similar pattern as in the early time window. This pattern does not resemble the LPC pattern in unimodal language switching (e.g., Liu et al., 2016; Martin et al., 2013), which is generally characterized by a larger positivity for switch than repetition trials over posterior sites, nor does this pattern resemble the switch-related negativity (e.g., Declerck et al., 2021; Peeters, 2020), generally characterized by a larger negativity across the scalp for switch than repetition trials.

To seek further support that the ERP language switching pattern observed here with bimodal bilinguals does not typically occur with unimodal bilinguals, we relied on our previous study with English-Spanish bilinguals that had a nearly identical design (Declerck et al., 2021). In that study, we found a switch-related negativity when the data for both languages were collapsed. Because the pattern in the current study was especially prevalent in only one language (ASL), we re-analyzed the language switching data of Declerck et al. (2021) for each language (English and Spanish) separately. The results showed no interaction between Trial type and Anterior/Posterior for either Spanish or English,[4] providing additional evidence that a pattern like the one observed in our bimodal language switching study does not seem to occur during unimodal language switching.

Our results leave open several questions, one being why we only observed significant ERP switch costs in ASL. Stronger evidence of language control during processing of the less dominant language (ASL in the current study; see Table 2) makes sense on a theoretical level (e.g., Green, 1998; Meuter and Allport, 1999). Because the more dominant language is used more often throughout daily life, it will accumulate a larger base activation and will typically interfere more when the less dominant language is being produced than vice versa. Subsequently, more control processes should be implemented during the production of the less dominant language. Previous ERP unimodal language switching studies have also found significant differences between switch and repetition trials only for the less dominant language, with different ERP components (i.e., N2 and LPC; e.g., Jackson et al., 2001; Liu et al., 2016; Martin et al., 2013; Zheng et al., 2020). So, along the lines of several unimodal language switching ERP studies, we suggest that the less dominant language (ASL in the current study) requires more control processes during bimodal language production.

Another open question is what the ERP switch cost pattern in ASL reflects. Since the pattern in the early time window mirrors the pattern in the late time window, we assume that both windows reflect a protracted effect that likely relies on the same underlying process. This protracted switch-related pattern in the ASL data, with an anterior switch-related positivity and a posterior switch-related negativity, seems to be a dipolar pattern, and thus is quite possibly associated with a single underlying process. Since the pattern observed here with bimodal bilinguals seems unique to this type of bilingual, we cannot explain the ASL pattern based on control processes that are typically discussed in the unimodal language control literature (e.g., language control at the lemma level as suggested by the ICM [Green, 1998]). Based on previous research, the dipolar pattern that we observed in these bimodal bilinguals might be a control process that is associated with managing vocal versus manual output (Kaufmann et al., 2018). While this would make sense in the late time window, it is not clear why such a control process would be engaged in the early time window, since it mainly relates to the final output processing stage. Nonetheless, it might very well be that bimodal bilinguals engage (some) language control as soon as it becomes clear which language to use, similar to unimodal bilinguals. This hypothesis would entail that bimodal language control at the output modality level (e.g., selection of the articulators) might be engaged in the early time window.

If this conjecture is true, then we might have to step away from the notion that unimodal bilingual models can be used to explain bimodal bilingual performance. Thus, models such as the ICM (1998), and any later versions of this model (e.g., Declerck et al., 2015; Green and Abutalebi, 2013), might not hold up entirely for bimodal bilinguals. More specifically, if what we propose here is correct, then unlike unimodal bilinguals, bimodal bilinguals do not rely on an inhibitory process at the lemma level, but rather at the output level. Future research will have to further investigate this claim.

Alternative explanations are of course possible. One such alternative explanation is that the observed ERP pattern is mainly due to (non-linguistic) modality switching (e.g., Philipp et al., 2013). This alternative explanation is difficult to dispel in any bimodal language switching study since sign language and spoken language are inherently connected to a different output modality. So, it is impossible to disconnect those languages from their modality. However, there are indications that our ERP results are capturing language control processes. For instance, similar to unimodal language switching (e.g., Jackson et al., 2001; Liu et al., 2016; Martin et al., 2013; Zheng et al., 2020), we observed larger switch-related ERP effects in the least dominant language (ASL in our study). While, to the best of our knowledge, no non-linguistic modality switching study has been conducted with ERPs, we assume that there would be little difference between vocal and manual switch and repetition trials in the ERPs.

Another possibility is that pre-stored semantic and/or phonological representations in specific modalities resulted in the observed ERP pattern. It seems unlikely to us that the semantic representations were somehow more connected to a modality within the scope of our study, since semantics is supposedly language independent, and thus most probably also modality-language independent. Furthermore, it is not entirely clear how this would cause our results. A more plausible argument could be made for phonological representations being connected to a modality, as each language has their own specific phonology. However, the phonology of the non-target language is co-activated in bimodal bilinguals (e.g., Lee et al., 2019; Meade et al., 2017). So, both ASL and English phonology are activated when accessing a word in either ASL or English, making it unlikely that this could be the main explanation for our results.

In sum, in this ERP study of bimodal language switching, no ERP patterns related to control were observed with the spoken language. Yet,

[4] Interaction of the factors Trial type and Anterior/Posterior in the unimodal language switching data of Declerck et al. (2021) per language: Early window (200–350 ms) English: $F(4, 92) = 2.36$, $p = .120$, $\eta p^2 = .093$; Spanish: $F(4, 92) = 0.08$, $p = .902$, $\eta p^2 = .003$. Late window (400–600 ms) English: $F(4, 92) = 1.67$, $p = .208$, $\eta p^2 = .068$; Spanish: $F(4, 92) = 1.17$, $p = .314$, $\eta p^2 = .048$.

during sign language production, a switch-related positivity over anterior sites and a switch-related negativity over posterior sites was observed. Since this pattern is not typically observed with unimodal bilinguals, we concluded that language control occurs differently between these two types of bilinguals. More specifically, we propose that bimodal bilinguals rely more on control processes between their two output modalities (i.e., vocal vs. manual), with a larger impact on the less dominant language (i.e., in this case sign language).

Author contributions

All authors helped with the conceptualization of the study and improved on the first draft. MD and GM analyzed the data. MD collected the data and wrote the first draft.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2021.108019.

References

Blanco-Elorrieta, E., Caramazza, A., 2021. A Common Selection Mechanism at Each Linguistic Level in Bilingual and Monolingual Language Production. Cognition, p. 104625.

Blanco-Elorrieta, E., Emmorey, K., Pylkkänen, L., 2018. Language switching decomposed through MEG and evidence from bimodal bilinguals. Proc. Natl. Acad. Sci. Unit. States Am. 115, 9708–9713.

Bonfieni, M., Branigan, H.P., Pickering, M.J., Sorace, A., 2019. Language experience modulates bilingual language control: the effect of proficiency, age of acquisition, and exposure on language switching. Acta Psychol. 193, 160–170.

Christoffels, I.K., Firk, C., Schiller, N.O., 2007. Bilingual language control: an event-related brain potential study. Brain Res. 1147, 192–208.

Costa, A., Caramazza, A., Sebastian-Galles, N., 2000. The cognate facilitation effect: implications for models of lexical access. J. Exp. Psychol. Learn. Mem. Cognit. 26, 1283–1296.

Costa, A., Miozzo, M., Caramazza, A., 1999. Lexical selection in bilinguals: do words in the bilingual's two lexicons compete for selection? J. Mem. Lang. 41, 365–397.

Costa, A., Santesteban, M., 2004. Lexical access in bilingual speech production: evidence from language switching in highly proficient bilinguals and L2 learners. J. Mem. Lang. 50, 491–511.

Costa, A., Santesteban, M., Ivanova, I., 2006. How do highly proficient bilinguals control their lexicalization process? Inhibitory and language-specific selection mechanisms are both functional. J. Exp. Psychol. Learn. Mem. Cognit. 32, 1057–1074.

Declerck, M., Ivanova, I., Grainger, J., Duñabeitia, J.A., 2020. Are similar control processes implemented during single and dual language production? Evidence from switching between speech registers and languages. Biling. Lang. Cognit. 23, 694–701.

Declerck, M., Koch, I., Philipp, A.M., 2012. Digits vs. pictures: the influence of stimulus type on language switching. Biling. Lang. Cognit. 15, 896–904.

Declerck, M., Koch, I., Philipp, A.M., 2015. The minimum requirements of language control: evidence from sequential predictability effects in language switching. J. Exp. Psychol. Learn. Mem. Cognit. 41, 377–394.

Declerck, M., Meade, G., Midgely, K.J., Holcomb, P.J., Roelofs, A., Emmorey, K., 2021. On the connection between language control and executive control – an ERP study. Neurobiology of Language 1–19.

Declerck, M., Philipp, A.M., 2015. A review of control processes and their locus in language switching. Psychon. Bull. Rev. 22, 1630–1645.

Dias, P., Villameriel, S., Giezen, M.R., Costello, B., Carreiras, M., 2017. Language switching across modalities: evidence from bimodal bilinguals. J. Exp. Psychol. Learn. Mem. Cognit. 43, 1828–1834.

Emmorey, K., Giezen, M.R., Gollan, T.H., 2016. Psycholinguistic, cognitive, and neural implications of bimodal bilingualism. Biling. Lang. Cognit. 19, 223–242.

Emmorey, K., Mott, M., Meade, G., Holcomb, P.J., Midgley, K.J., 2021. Lexical selection in bimodal bilinguals: ERP evidence from picture-word interference. Language, Cognition and Neuroscience 36, 840–853.

Emmorey, K., Li, C., Petrich, J., Gollan, T.H., 2020. Turning languages on and off: switching into and out of code-blends reveals the nature of bilingual language control. J. Exp. Psychol. Learn. Mem. Cognit. 46, 443–454.

Giezen, M.R., Blumenfeld, H.K., Shook, A., Marian, V., Emmorey, K., 2015. Parallel language activation and inhibitory control in bimodal bilinguals. Cognition 141, 9–25.

Giezen, M.R., Emmorey, K., 2016. Language co-activation and lexical selection in bimodal bilinguals: evidence from picture–word interference. Biling. Lang. Cognit. 19, 264–276.

Green, D.W., 1998. Mental control of the bilingual lexico-semantic system. Biling. Lang. Cognit. 1, 67–81.

Green, D.W., Abutalebi, J., 2013. Language control in bilinguals: the adaptive control hypothesis. J. Cognit. Psychol. 25, 515–530.

Jackson, G.M., Swainson, R., Cunnington, R., Jackson, S.R., 2001. ERP correlates of executive control during repeated language switching. Biling. Lang. Cognit. 4, 169–178.

Kang, C., Ma, F., Li, S., Kroll, J.F., Guo, T., 2020. Domain-general inhibition ability predicts the intensity of inhibition on non-target language in bilingual word production: an ERP study. Biling. Lang. Cognit. 5, 1056–1069.

Kaufmann, E., Mittelberg, I., Koch, I., Philipp, A.M., 2018. Modality effects in language switching: evidence for a bimodal advantage. Biling. Lang. Cognit. 21, 243–250.

Kaufmann, E., Philipp, A.M., 2017. Language-switch costs and dual-response costs in bimodal bilingual language production. Biling. Lang. Cognit. 20, 418–434.

Lee, B., Meade, G., Midgley, K.J., Holcomb, P.J., Emmorey, K., 2019. ERP evidence for co-activation of English words during recognition of American Sign Language signs. Brain Sci. 9, 148.

Liu, H., Liang, L., Dunlap, S., Fan, N., Chen, B., 2016. The effect of domain-general inhibition-related training on language switching: an ERP study. Cognition 146, 264–276.

Lu, A., Wang, L., Guo, Y., Zeng, J., Zheng, D., Wang, X., Shao, Y., Wang, R., 2019. The roles of relative linguistic proficiency and modality switching in language switch cost: evidence from Chinese visual unimodal and bimodal bilinguals. J. Psycholinguist. Res. 48, 1–18.

Ma, F., Li, S., Guo, T., 2016. Reactive and proactive control in bilingual word production: an investigation of influential factors. J. Mem. Lang. 86, 35–59.

Macizo, P., Bajo, T., Paolieri, D., 2012. Language switching and language competition. Sec. Lang. Res. 28, 131–149.

Martin, C.D., Strijkers, K., Santesteban, M., Escera, C., Hartsuiker, R.J., Costa, A., 2013. The impact of early bilingualism on controlling a language learned late: an ERP study. Front. Psychol. 4, 815.

Massa, E., Köpke, B., El Yagoubi, R., 2020. Age-related effect on language control and executive control in bilingual and monolingual speakers: behavioral and electrophysiological evidence. Neuropsychologia 138, 107336.

Meade, G., Grainger, J., Holcomb, P.J., 2019. Task modulates ERP effects of orthographic neighborhood for pseudowords but not words. Neuropsychologia 129, 385–396.

Meade, G., Midgley, K.J., Dijkstra, T., Holcomb, P.J., 2018. Cross-language neighborhood effects in learners indicative of an integrated lexicon. J. Cognit. Neurosci. 30, 70–85.

Meade, G., Midgley, K.J., Sehyr, Z.S., Holcomb, P.J., Emmorey, K., 2017. Implicit co-activation of American Sign Language in deaf readers: an ERP study. Brain Lang. 170, 50–61.

Meuter, R.F., Allport, A., 1999. Bilingual language switching in naming: asymmetrical costs of language selection. J. Mem. Lang. 40, 25–40.

Peeters, D., 2020. Bilingual switching between languages and listeners: insights from immersive virtual reality. Cognition 195, 104107.

Peeters, D., Dijkstra, T., 2018. Sustained inhibition of the native language in bilingual language production: a virtual reality approach. Biling. Lang. Cognit. 21, 1035–1061.

Philipp, A.M., Weidner, R., Koch, I., Fink, G.R., 2013. Differential roles of inferior frontal and inferior parietal cortex in task switching: evidence from stimulus-categorization switching and response-modality switching. Hum. Brain Mapp. 34, 1910–1920.

Roelofs, A., 1998. Lemma selection without inhibition of languages in bilingual speakers. Biling. Lang. Cognit. 1, 94–95.

Roelofs, A., Piai, V., Garrido Rodriguez, G., Chwilla, D.J., 2016. Electrophysiology of cross-language interference and facilitation in picture naming. Cortex 76, 1–16.

Schwieter, J.W., Sunderman, G., 2008. Language switching in bilingual speech production: In search of the language-specific selection mechanism. Ment. Lexicon 3, 214–238.

Thierry, G., Wu, Y.J., 2007. Brain potentials reveal unconscious translation during foreign-language comprehension. Proc. Natl. Acad. Sci. Unit. States Am. 104, 12530–12535.

Timmer, K., Calabria, M., Costa, A., 2019. Non-linguistic effects of language switching training. Cognition 182, 14–24.

Verhoef, K., Roelofs, A., Chwilla, D.J., 2009. Role of inhibition in language switching: evidence from event-related brain potentials in overt picture naming. Cognition 110, 84–99.

Zheng, X., Roelofs, A., Erkan, H., Lemhöfer, K., 2020. Dynamics of inhibitory control during bilingual speech production: an electrophysiological study. Neuropsychologia 140, 107387.