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The source of attention modulations in bilingual language contexts

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ABSTRACT

Bilinguals who switch from a monolingual context to a bilingual context enhance their domain-general attentional system. But what drives the adaptation process and translates into the observed increased efficiency of the attentional system? To uncover the origin of the plasticity in a bilingual's language experience, we investigated whether switching between other types of categories also modulated domain-general attentional processes. We compared performance of Catalan-Spanish bilinguals across three experiments in which participants performed the Attentional Network Test in a mixed context and in two single contexts that were created by interleaving words with flankers. The contexts were related to switching (or not) between languages (Experiment-1) or between low-level perceptual color categories (Experiment-2) or between linguistic categories (Experiment-3). Both switching between languages and linguistic categories revealed increased target-P3 amplitudes in mixed contexts compared to single contexts. These findings can inform the Inhibitory Control model regarding the locus and domain-generality of attentional adaptations.

1. Introduction

Every day, bilinguals move between different types of language contexts. For example, bilinguals can move from a monolingual context (such as reading a novel in Spanish) to a bilingual context (such as reading a text message from a Catalan friend while reading a Spanish book). This shows that language context can change rapidly, which in turn requires quick adaptation of the cognitive system. Understanding how bilinguals manage two languages is relevant, given that changes in language context are very frequent and rapid in the modern world (i.e., information on the internet in different languages). Previous research has indicated that the efficiency of domain-general mechanisms is enhanced in a bilingual language context compared to a monolingual one (Jiao et al., 2019; Kałamała et al., 2020; Timmer, Calabria, & Costa, 2019; Wu & Thierry, 2013; Yang, Ye, Wang, Zhou, & Wu, 2018; for a review see Wodniecka et al., 2020). Yet, which exact mechanisms change rapidly is still poorly understood. So, what drives the adaptation process and translates into the observed increased efficiency of the attentional system? To uncover the origin of the plasticity in bilingual contexts, we investigated whether other higher-order processes or lower-level variability in the perceptual environment, both of which are related to switching, also reveal these short-term adaptations (i.e., functional changes by which a person becomes better tuned to their environment) in the domain-general attentional system. To capture the complexity of the network of sub-mechanisms of the attentional system, we looked at the Attentional Network Test (ANT). In this task, participants indicated the direction (left or right) of the central arrow of five arrows (i.e., flanker task; Posner, 1980), which was sometimes preceded by a cue (asterisks) that indicated the appearance or location of the upcoming flanker (ANT task; MacLeod et al., 2010; Posner & Fan, 2004).

1.1. How language context modulates domain-general attention and control

How does our general attentional system manage constantly changing linguistic input? Specifically, how are attentional mechanisms adjusted depending on whether we are in a bilingual or a monolingual situation? It has been suggested that long-term bilingual language experience impacts domain-general control and attentional processes (Bialystok, 2017). Bilinguals who switch often between languages in

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their daily life, compared to those who do not, were more efficient in switching between color and shape decisions (i.e., local control; Hartanto & Yang, 2016). On top of this, simultanous interpreters showed different efficiency in global control over bilinguals in mixed- compared to single-language situations. Specifically, during task switching, interpreters showed a mixing cost (Babcock & Vallesi, 2017) and an n-2 repetition cost (Babcock & Vallesi, 2015) advantage. However, the same bilingual can switch language context daily, which might mean that domain-general processes can also be modulated in the short-term. Recently, there has been an increase in the amount of research investigating the impact of short-term language context modulations on attentional control tasks (for a review see Wodniecka et al., 2020). Most studies reveal that the efficiency of domain-general attentional control processes is enhanced in a bilingual compared to a monolingual context (e.g., Jiao et al., 2019; Timmer, Calabria, & Costa, 2019; Wu & Thierry, 2013; Yang, Ye, Wang, Zhou, & Wu, 2018).

The goal of the present study is to elucidate which sub-mechanism of attentional control initiates the rapid adjustments. Previous studies compared the impact of bilingual vs. monolingual language context on performance in a flanker task, but each reached different conclusions. Wu and Thierry (2013) observed that the bilingual context was related to a smaller difference between incongruent and congruent trials, which led them to conclude that the bilingual context enhances *conflict resolution*. Jiao et al. (2019), on the other hand, observed that the bilingual context was related to overall faster responses and, on the basis of this finding, these researchers inferred that the bilingual context enhances *conflict monitoring*. Clearly, both conflict monitoring and conflict resolution are employed when performing domain-general control tasks like the flanker task (Posner, 1980; Posner & Fan, 2004). When different types of trials (i.e., congruent and incongruent) are intermixed, there is a demand to continuously monitor the requirements for upcoming stimuli and detect changes in conflict-related demands (conflict monitoring). If conflict is detected, this is consequently resolved by taking specific actions to resolve conflict on incongruent trials (conflict resolution) (Costa, Hernández, Costa-Faidella, & SebastiáGallés, 2009; Timmer, Wodniecka, & Costa, 2021). An important goal within studies on bilingualism is to better understand the language demands under which these two mechanisms can be triggered and enhanced.

To explore why sometimes conflict monitoring and other times conflict resolution are impacted by a bilingual context, the experiments in the current study used ANT instead of the flanker task. In the ANT task, cues precede the target stimulus. Through manipulation of the cues, we can measure earlier attentional mechanisms, like alerting (i.e., achieving and maintaining an alert state) and orienting (i.e., directing attention to sensory effects in our surroundings) in ANT (MacLeod et al., 2010; Posner & Fan, 2004). To get a more sensitive measure of the sub-mechanisms, we combined behavioral with electroencephalography (EEG) measures (Asanowicz, Wołoszyn, Panek, & Wronka, 2019; Neuhaus et al., 2010). The efficiency of executive control is reflected in modulations of the target-P3 component (Wu & Thierry, 2013).[2] Target-P3 modulations within the executive control network reflect the underlying mechanisms of both conflict monitoring and conflict resolution (Neuhaus et al., 2010). The efficiency of alerting and orienting is reflected by target-P3 and impacts earlier ERP components such as target-N1. Target-N1 indexes processing of upcoming information, which is enhanced in cued compared to uncued trials (Asanowicz et al., 2019; Neuhaus et al., 2010). This is followed by target-P3 modulations, a neural signature that is elicited in a wide range of paradigms that require target detection when attentional and memory mechanisms are engaged (Polich, 2007). In other words, target-P3 indexes how higher-order attention interacts with other cognitive processes.

In our previous study, we found that a bilingual context (i.e., with words from different languages interleaved between the flankers) enhanced both *conflict monitoring* (both congruent and incongruent trials) and the attentional effect of *alerting* (both cue and no-cue trials), as reflected in increased target-P3 amplitudes compared to monolingual contexts (Timmer et al., 2021; also Experiment 1 of the current article). The fact that we observed target-P3 modulation in bilingual contexts for both alerting as well as conflict-monitoring measures suggests that the origin of enhanced attentional processing in bilingual contexts starts earlier than previously suggested (i.e., during conflict resolution or inhibition) (Wu & Thierry, 2013; Yang et al., 2018). Both alerting and conflict monitoring are aspects of attention which help efficient processing of incoming information and prepare one for potential conflict in the environment (conflict resolution). The idea that conflict monitoring originates earlier is supported by increased target-N1 amplitudes for all kinds of arbitrary alerting cues that precede stimuli in simple interference tasks (Asanowicz, Wołoszyn, Panek, & Wronka, 2019; Böckler, Alpay, & Stürmer, 2010; Jepma, Wagenmakers, Band, & Nieuwenhuis, 2009; Neuhaus et al., 2010). We showed that language switches revealed a similar target-N1 to language repetitions in a bilingual language context (see Fig. 5). This supports the idea that language switches have an alerting function and bring the brain to a state of alertness in order to process further incoming information. This is in line with recent models of bilingualism which suggest that executive control operates through earlier attentional mechanisms, such as monitoring (Dong & Li, 2020).

However, we still do not know the nature of increased attentional efficiency in the bilingual context (as opposed to the monolingual one). To address this issue, in the current paper we compare the results of our previous study (Timmer et al., 2021) with two follow-up experiments that investigated whether different aspects of context lead to similar ERP effects, thus suggesting a similar type of attentional adaptions.

1.2. *The origin of language context modulations*

Why does a bilingual language context modulate the attentional network? Is the observed attention adaption specific to the bilingual experience? Attention adaptations could be specifically related to switching between languages; alternatively, attention adaptations could be related to some earlier perceptual processes triggered by differences in some features of stimuli.

Within models of language production, the origin of enhanced domain-general processing was originally suggested to stem from increased involvement of inhibitory control during bilingual language production (for a review see Bialystok, 2017). Thanks to the inhibitory control system (Green, 1998), bilinguals can select words from the intended language without many intrusions from their counterparts in the unintended language (Gollan, Sandoval, & Salmon, 2011; Poulisse, 1999). However, more recent work has also claimed that this enhancement can be attributed to the requirement to monitor one's language context to detect potential language switches, which require 'resetting' the brain for a different language scheme to achieve effective communication in a bilingual context (Costa, Hernández, Costa-Faidella, & Sebastián-Gallés, 2009). Evidence for this comes from group comparisons between monolinguals and bilinguals that showed enhanced conflict monitoring in the ANT task (Costa, Hernández, & Sebastián-Gallés, 2008; Marzecová, Bukowski, et al., 2013; Marzecová, Asanowicz, Krivá, & Wodniecka, 2013; Tao, Marzecová, Taft, Asanowicz, & Wodniecka, 2011). This process of monitoring in order to prioritize a specific language occurs before the suppression of the irrelevant language.

We suggest that the origin of language context modulations of attentional control could either be at the stage of enhanced *conflict monitoring* of the language context or at the even earlier and more general attentional process of *alertness*, which is potentially related to changes in stimuli in the environment. Bilinguals can make efficient use of cues in their environment that indicate the language in which they

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[2] Note, it is the subcomponent P3b that is modulated due to differences in processing of incoming information (see Polich, 2007, for a review). However, we will refer to the broad term, target-P3, throughout the manuscript.

should speak (Timmer, Grundy, & Bialystok, 2017b). For example, a socio-cultural (e.g., Asian or Caucasian) or known face can activate the target language in which one needs to speak (Blanco-Elorrieta & Pylkkänen, 2017; Esti Blanco-Elorrieta & Liina Pylkkänen, 2017; Cong Liu, Timmer, Jiao, Yuan, & Wang, 2019). A word in a specific language can also activate the language in which one needs to speak. This shows the importance of investigating not only the impact that production has on attention (which is more often researched and discussed) but also the impact comprehension has on attention (e.g., reading words in different languages). Wu and Thierry (2013) were the first to show that different language comprehension contexts can indeed also impact the domain-general system.

If the domain-general enhancement observed in previous studies that focused on the impact of comprehension contexts is driven by lower-level perceptual changes between words from different languages (e.g., -d ending in Spanish or -t ending in Catalan), then we would speculate that we should also find attentional enhancements with other low-level changes, such as color changes. However, the enhancement of attention that is observed in bilingual contexts could also be driven by the identification of languages (L1 vs. L2). Language identification requires involvement of higher-order categorization processes. If the origin of enhancement is related more to these higher-order processes, other types of processes that require categorization (e.g., linguistic categories like nouns and verbs) even within one language could also impact attentional control. Previous studies have shown that within-language switching (i.e., naming pictures as nouns/objects or verbs/actions) reveals both differential and overlapping patterns of activation with between-language switching (i.e., naming pictures in different languages) (Abutalebi et al., 2013; Cattaneo, Costa, Gironell, & Calabria, 2020; Khateb et al., 2007). While between-language switching has a need for interference control, both between-context and within-context switching require monitoring of the language context as part of a more general task monitoring system. Therefore, if the underlying mechanism involves more general alertness and monitoring, then a requirement to switch between nouns and verbs within one language might also impact domain-general attentional processes.

The idea that language monitoring can impact domain-general processes is supported by the finding that self-monitoring of speech production at least partly overlaps with monitoring of non-linguistic tasks (Acheson, Ganushchak, Christoffels, & Hagoort, 2012; Ganushchak & Schiller, 2006, 2008; Riès, Janssen, Dufau, Alario, & Burle, 2011). Indeed, different monitoring tasks (verbal and non-verbal) reveal that the same brain mechanisms are responsible for the ability to monitor stimuli in the environment, regardless of their characteristics (Ambrosini, Arbula, Rossato, Pacella, & Vallesi, 2019; Ambrosini, Capizzi, Arbula, & Vallesi, 2020). Importantly, a task that required monitoring but did not involve language (i.e., interference resolution training through the n-back task), also impacted participants' efficiency in the ANT task, as reflected by increased target-P3 amplitudes and enhanced processing speed after training (Oelhafen et al., 2013). Moreover, increases in target-P3 amplitudes for alerting and monitoring were also found after acute physical exercise (Chang, Chu, Wang, Song, & Wei, 2015). The authors suggest that exercise enhances arousal, which allows more resources to be allocated to task-relevant stimuli. The alerting effect in the ANT task has been suggested to underlie brief increments in arousal (Luna, Roca, Martín-Arévalo, & Lupiáñez, 2020). Thus, activating either non-linguistic monitoring or more general arousal improves both alertness and monitoring. If target-P3 amplitudes increase in the ANT task in a bilingual context (Timmer et al., 2021), we believe the enhancement of brain functioning has its origin in a more general alertness and monitoring. Therefore, we would also expect to find this in other linguistic contexts that modulate monitoring demands.

1.3. The current study

To further investigate the origin of attentional modulation following a bilingual language context, we directly compared the results of a bilingual language context (Experiment 1; Timmer et al., 2021) with two follow-up experiments in which we manipulated low-level variability by changing the ink color of words (Experiment 2), and we manipulated higher-order categorization by changing the linguistic word type between nouns and verbs (Experiment 3).

In all three experiments, Catalan-Spanish participants performed the ANT task, in which they indicated the direction (left or right) of the central arrow of five arrows (i.e., flankers) (Posner, 1980). A preceding cue (asterisks) that sometimes occurred before the flanker indicated the appearance or location of the upcoming flanker. This test reliably measures three aspects of attentional processes of *executive control* (i.e., resolving response conflict by inhibiting competing responses), *alerting* (i.e., achieving and maintaining an alert state), and *orienting* (i.e., directing attention to sensory effects in our surroundings) (MacLeod et al., 2010; Posner & Fan, 2004). These neural constructs were indirectly measured by behavioral (reaction times) and electrophysiological measures. Each network is measured by a comparison: efficiency in *executive control* (or conflict resolution) is manifested as a smaller difference between incongruent and congruent trials; *alerting* is measured by the difference between cue and no-cue trials; *orienting* is measured by the difference between spatial cues, which provide information regarding the location of the flanker, and alerting cues, which do not provide information regarding the location.

To manipulate the context that modulates the ANT task, we interleaved words between each cue-flanker trial in all experiments. Crucially, manipulations of these words created two single contexts and one mixed context in each experiment. In the bilingual experiment, words were presented in one language (e.g., Catalan; single context) or in two languages (Catalan and Spanish; mixed context). In the color experiment, we manipulated color rather than language context by presenting Catalan words in red (or blue) only (single contexts) or in red and blue (mixed context). In the word-type experiment, we manipulated word type by presenting Catalan nouns (or verbs) only (single contexts) or mixed Catalan nouns and verbs (mixed context) (see Fig. 1). This allowed us to assess whether single vs mixed contexts modulate the three attentional networks.

The experiment in which we manipulated the context by mixing (or not) two languages (Experiment 1) revealed ERP modulations with greater target-P3 amplitudes in the bilingual context than in the monolingual context in both the alerting and executive control networks, thus indicating an overall heightened attention state. Therefore, our special focus in the follow up experiments was on modulations of target-P3 in response to mixed vs single contexts in the color and word-type experiments. We expected both the executive control network and the alerting network to increase target-P3 amplitudes in mixed contexts. This target-P3 increase indexes enhanced attentional processing.

2. Method

2.1. Participants

All participants were balanced, high-proficiency Catalan-Spanish bilinguals with good knowledge of English as L3 and were paid for their participation. All of them had normal or corrected-to-normal vision and no history of neurological impairments or language disorders. To assess language proficiency and usage, participants completed the Bilingual Language Profile (BLP) questionnaire (Birdsong, Gertken, & Amengual, 2012) before being invited to the experiment[3] and a self-rating language proficiency and social economic background questionnaire during the experiment. To assess nonverbal intelligence, participants also executed Superior Scale I of Raven's Advanced Progressive Matrices (Raven,

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[3] While all participants completed the BLP before being invited to take part in the experiment, two participants' data from the BLP were lost in experiment 1.

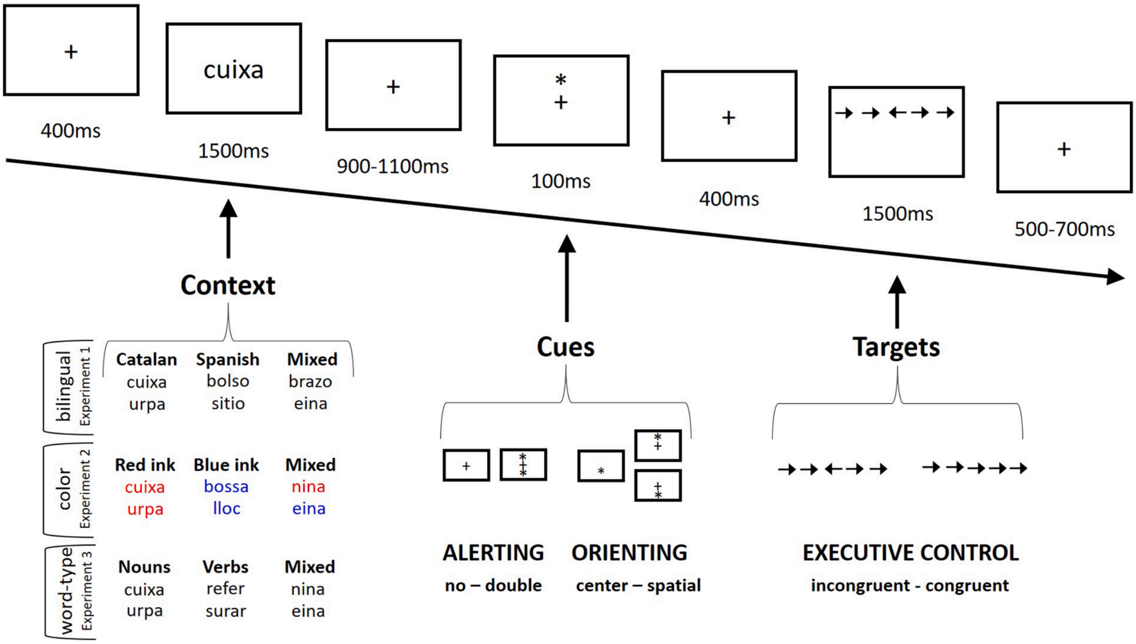

Fig. 1. An example of a trial within each of the three experiments. In the bilingual experiment (1), single contexts are created by words in Catalan or Spanish only, while the mixed contexts included both languages. In the color experiment (2), the words in all three contexts were in Catalan, and the context was manipulated by presenting all words in one ink color (red ink or blue ink) or by mixing both colors (mixed context). In the word-type experiment (3), all words were also in Catalan; in the single contexts, only nouns or only verbs are presented, while these were varied in the mixed context. Cues and targets were the same across all three experiments. Cues reflect the alerting (no cue vs double cue) and orienting networks (central cue vs spatial cue). Targets are (in)congruent flankers that reflect the executive control network.

Raven, & Court, 1998).

Eighty-four participants were divided between the three experiments: the bilingual experiment, the color experiment, and the word-type experiment. In the bilingual context experiment, seven of the 30 participants were excluded from the analysis: six due to malfunctioning of the EEG equipment or excessive artifacts, and one due to technical problems with the PC. This left 23 participants in the group (11 females; average age: 22.4 years; SD = 2.50). In the color experiment, five of the 27 participants were excluded due to excessive artifacts in the EEG signal. This left 22 participants in the color group (17 females; average age: 21.7 years; SD = 2.14). In the word-type experiment, six of the 27 participants were excluded: four due to excessive EEG artifacts, one due to malfunctioning of the flat electrode on the mastoid, and one due to technical problems with recording the behavioral responses. This left 21 participants in the word-type group (18 females; average age: 21.4 years; SD = 1.87).

The self-rating language proficiency and social economic background questionnaire showed that participants from the three experiments did not differ in terms of their Catalan and Spanish proficiency and Age of Acquisition; neither did they differ in terms of their parents' education level, which is an index of social-economic status (all p's $<$ 0.1; see Table 1). In addition, all participants completed Superior Scale I of Raven's Advanced Progressive Matrices, which reflects nonverbal intelligence (Raven, Raven, & Court, 1998).[4] Their scores also did not differ between the experimental groups (see Table 1). Further, participants were Catalan-Spanish bilinguals who rated their proficiency equally on reading, writing, and listening between languages (all p's $<$ 0.1), but they felt more comfortable speaking Catalan than Spanish ($t(70) = 2.02$, $MSe = 0.77$, $p < .05$; see Table 1). Furthermore, they used both Catalan and Spanish in all kinds of situations (i.e., with friends and family and at school or work). However, in each situation they used more Catalan than Spanish (all p's $<$ 0.001) and more Spanish than other languages (all p's $<$ 0.001). There were no differences in language usage between participants in the three experiments (all p's $>$ 0.321).

2.2. Materials

Flanker stimuli consisted of five horizontal arrows, of which the central arrow pointed either left or right and the flanking arrows all pointed in the same direction (congruent) or in the opposite direction (incongruent trials).

Word stimuli consisted of 576 high-frequency words in either Catalan or Spanish (bilingual experiment) or only in Catalan (color and word-type experiment). Within each experiment, the words were distributed over three context blocks (two single blocks and one mixed block). For the bilingual context experiment, half of the words were Catalan and the other half were Spanish words. For the bilingual context experiment, the words were presented in either Catalan, Spanish (single blocks), or in both languages (mixed block) (for more details see Timmer, Wodniecka, & Costa, 2021). For the color and word-type experiments, all words were presented in Catalan. For the color context, words were presented only in blue or only in red ink (single blocks), or both colors were mixed (mixed block). For the word-type context, only nouns or verbs were presented (single blocks) or they were intermixed (mixed block). Word length was on average 6.16; word frequency was on average 33.52, as measured by the Busca Palabras database (Davis & Perea, 2005). The single versus mixed blocks were matched on all the above-mentioned variables (all t's $<$ 1). Some words were avoided due to possible semantic interference with the flanker task (e.g., left or right). In addition, words with affective valence were also excluded (Bradley & Lang, 1999).

2.3. Procedure and design

Participants were seated approximately 1 m from the computer

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[4] In this task, participants saw 12 matrices, each of which had one piece missing (shown by an empty space). For each matrix, participants had to select which of eight possible pieces fitted the empty space.

Table 1
Mean answers (and standard errors) on the self-rating language proficiency and social economic background questionnaire as well as on the Bilingual Language Profile (BLP) questionnaire (Birdsong, Gertken, & Amengual, 2012).

		Experiments		
		Bilingual (N = 23)	Color (N = 22)	Word type (N = 21)
Catalan	Age of Acquisition	1.22 (0.33)	0.68 (0.34)	1.29 (0.35)
	Speaking [a]	6.7 (0.12)	6.8 (0.11)	6.8 (0.09)
	Listening [a]	6.9 (0.07)	6.8 (0.08)	7.0 (0.00)
	Reading [a]	6.9 (0.06)	6.8 (0.13)	6.9 (0.05)
	Writing [a]	6.6 (0.14)	6.6 (0.18)	6.7 (0.10)
Spanish	Age of Acquisition	1.57 (0.32)	1.18 (0.33)	1.10 (0.33)
	Speaking [a]	6.6 (0.15)	6.6 (0.13)	6.6 (0.13)
	Listening [a]	6.8 (0.09)	6.8 (0.11)	6.9 (0.05)
	Reading [a]	6.8 (0.08)	6.7 (0.14)	6.9 (0.08)
	Writing [a]	6.6 (0.14)	6.7 (0.12)	6.7 (0.10)
	Education level of parents [b]	4.0 (0.32)	4.1 (0.28)	4.5 (0.20)
	Raven's intelligence test [c]	8.8 (0.40)	8.9 (0.39)	9.9 (0.38)
BLP	Using Catalan with friends [d]	58.09 (5.1)	57.73 (5.1)	61.91 (5.2)
	Using Spanish with friends [d]	35.24 (4.4)	33.64 (4.3)	35.24 (4.5)
	Using other languages with friends [d]	9.52 (1.9)	5.91 (1.8)	4.29 (1.9)
	Using Catalan with family [d]	67.62 (7.5)	65.91 (7.4)	62.86 (7.5)
	Using Spanish with family [d]	26.67 (7.1)	33.18 (6.9)	36.19 (7.1)
	Using other languages with family [d]	5.24 (2.2)	0.91 (2.2)	0.95 (2.2)
	Using Catalan at school/work [d]	56.67 (5.6)	55.91 (5.5)	54.29 (5.6)
	Using Spanish at school/work [d]	31.91 (4.7)	34.09 (4.6)	30.48 (4.7)
	Using other languages at school/work [d]	19.05 (4.4)	10.00 (4.3)	15.24 (4.4)

[a] 7-point scale, with 1 point being the lowest and 7 points being the highest self-rated proficiency.

[b] A 6-point scale, with 1 point being the lowest and 6 the highest education level, as averaged over both parents.

[c] Raw score out of a maximum score of 12.

[d] Percentage of time using a specific type of language in a normal week (BLP questionnaire).

screen in a quiet room with dimmed lights. First, each participant signed a written consent form. Second, they filled out the self-rating questionnaire. Third, they completed Raven's nonverbal intelligence test. Fourth, they performed the experimental Attentional Network Task (ANT). The procedure and design of Experiments 2 and 3 was the same as in Experiment 1 (Timmer et al., 2021). The trial sequence included 1) fixation cross (400 ms), 2) word (1500 ms), 3) fixation cross (jittered 1400–1600 ms), 4) (no) cue (asterisk; 100 ms), 5) blank screen (400 ms), and 5) flanker (1500 ms maximum), 6) ITI fixation (jittered 500–700 ms).

There was either no cue or the cue could be presented in the middle (center), above and below the fixation cross (double), or only above or below the center (spatial), but it always predicted the location of the flanker. Compared to the absence of a cue (i.e., no-cue condition), the double cue provided temporal information about the appearance of the target flanker (alerting network); compared to the central cue, which was always presented below or above the center, the spatial cue provided additional information regarding the location of the flanker (orienting). All other stimuli were presented in the center of the screen. See Materials for a description of the flanker and word conditions. Participants only had to respond to the central stimulus in the flanker task and indicate whether the central arrow pointed to the left or right by means of a corresponding button press, while no response to the words was required. See Fig. 1 for an overview of the trial procedure for each of the three experiments.

Each participant saw 576 trials divided over three blocks of 192 trials each. Each participant saw each word once and words were randomized between participants by means of 18 experimental stimulus sequences. In addition, block order was counterbalanced between participants, who could take a short break between the experimental blocks. Each block referred to either one of two single contexts or a mixed context. In Experiment 1, the context manipulation was between a single language and two mixed languages. In Experiment 2, one ink color was contrasted with two ink colors; in Experiment 3, a single word type was contrasted with intermixed nouns and verbs. Before the first block, 16 practice trials were presented so participants could get familiarized with the task.

2.4. *Electrophysiological recordings and analysis*

Using 64 Ag/AgCl electrodes distributed according to the 10–20 system, the electroencephalogram (EEG) signals were continuously registered and sampled at 512 Hz with Biosemi. The EEG data were preprocessed with Brain Vision Analyzer. The eye movements were monitored for eyeblinks (above and below the left eye) and horizontal eye movements (at the external canthus of the left eye) using four flat-type electrodes. Offline referencing was applied to the left mastoid and was online re-referenced to the average of the left and right mastoids. During testing, electrode impedance was kept below 10 Ω. A high-pass filter of 0.01 Hz/12 dB, a low-pass filter of 40 Hz/24 dB, and a notch filter of 50 Hz were applied. Artifacts were removed for data containing amplitudes below −150 μV or above + 150 μV, a voltage step of 150 μV within 200 ms, or activity below 0.5 μV in an interval of 100 ms. This was done after correcting ocular artifacts with Independent Component Analysis (ICA). Segmentation was done separately for the inhibition and alerting/orienting networks. All segments were averaged and baseline corrected from −300 to −100 pre-cue, during which participants saw a fixation cross in all conditions.

3. Results

Incorrect responses (2.5% of the data) and outliers (2.5 SD below/above the average per participant per condition; 2.5% of the data) were discarded from the analysis. This left a total of 94.9% of the trials in the analysis of response latencies. Due to the highly accurate scores and the lack of theoretical predictions for accuracy data, only descriptive data of the accuracy are provided (see Table 2). The RTs were examined with a 4-way ANOVA that included the within-subjects factors Cue Type (no cue vs. central cue vs. double cue vs. spatial cue), Congruency (congruent vs. incongruent), and Context (single1 vs. single2 vs. mixed), and the between-subjects factor Experiment (bilingual, color, and word type). The 4-way ANOVA was followed by analyses of the three attentional networks (alerting, orienting, and executive control).

3.1. *Behavioral results (response latencies)*

3.1.1. *General analyses*

Repeated measures analysis of variance showed a main effect of Congruency ($F(1,63) = 1015.88$, $MSe = 2199.87$, $p < .001$, $\eta_p^2 = 0.942$) and Cue Type ($F(3,189) = 189.57$, $MSe = 1807.50$, $p = .001$, $\eta_p^2 = 0.751$). In addition, there was an interaction between Congruency and Cue Type ($F(3,66) = 13.13$, $MSe = 504.74$, $p < .001$, $\eta_p^2 = 0.172$). None

Table 2
Mean reaction times in ms (and standard error) and mean accuracy in percentages (and standard error); separated for Experiment, Congruency, and Cues. EXP stands for experiment.

		no cue		central cue		double cue		spatial cue	
	EXP	congruent	incongruent	congruent	incongruent	congruent	incongruent	congruent	incongruent
RT (ms)	bilingual	492 (11)	565 (12)	455 (11)	541 (12)	450 (11)	540 (12)	435 (10)	502 (12)
	color	518 (11)	584 (12)	493 (11)	560 (12)	482 (11)	555 (12)	464 (10)	526 (12)
	word-type	518 (12)	585 (13)	496 (12)	579 (12)	481 (11)	572 (12)	461 (11)	537 (12)
ACC (%)	bilingual	98.9 (0.29)	94.0 (0.76)	98.7 (0.42)	92.3 (0.85)	99.0 (0.31)	93.1 (1.1)	98.7 (0.32)	95.3 (0.66)
	color	99.6 (0.30)	97.1 (0.78)	99.4 (0.43)	96.7 (0.86)	99.5 (0.32)	95.3 (1.1)	99.4 (0.32)	97.7 (0.68)
	word-type	99.4 (0.31)	97.6 (0.80)	99.2 (0.44)	97.2 (0.89)	99.5 (0.33)	95.8 (1.2)	99.3 (0.33)	97.8 (0.70)

of the other main effects or interactions were significant (all $Fs < 2.80$).

While there is a congruency effect under all cuing conditions (all p's < 0.001), the nature of the interaction between Congruency and Cue type comes from an enhanced cueing effect when subjects were given alerting cues (central and double cues) that contained no spatial information. Thus, the congruency effect is greater for the central (79 ms; SE $= 2.79$) and double (84 ms; SE $= 3.41$) cues than for the no (69 ms; SE $=$ 3.05) and spatial (68 ms; SE $= 2.98$) cues (all p's < 0.005). However, no differences were observed between the alerting cues ($t(66) = -2.00$, MSe $= 2.77$, ns) or between the no cue and spatial cue ($t < 1$) with Bonferroni correction.

3.1.2. *Assessing the three attentional networks*

The **alerting network** was represented by slower responses to no-cue trials (544 ms; SE $= 6.78$) than to double-cue trials (513 ms; SE $= 6.44$; $F(1,63) = 233.64$, $MSe = 391.91$, $p < .001$, $\eta_p^2 = 0.788$). There were no other main effects or interactions (all F's < 1.73). The **orienting network** was represented by slower responses for central (521 ms; SE $=$ 6.62) than spatial-cue trials (488 ms; SE $= 6.36$; $F(1,63) = 129.96$, MSe $= 834.84$, $p < .001$, $\eta_p^2 = 0.674$). There were no other main effects or interactions (all F's < 2.88). The **executive control network** (congruency effect) was represented by slower responses to incongruent flankers (553 ms; SE $= 6.79$) than to congruent flankers (479 ms; SE $= 6.19$; $F(1,63) = 1015.88$, $MSe = 2199.87$, $p < .001$, $\eta_p^2 = 0.942$). There were no other main effects or interactions (all F's < 2.28).

3.2. *Electrophysiological results*

3.2.1. *Alerting network*

The analysis consisted of the within-subjects factors Alerting (no cue vs. double cue) and Context (single1 vs. single2 vs. mixed), as well as the between-subjects factor Experiment (bilingual, color, vs. word type) throughout the parietal region (pooled over 9 electrodes: CP1, CPz, CP2, P1, Pz, P2, O1, Oz, O2). See Fig. 2 for the Context effect.

Target-N1 (180–220 ms after target). Target-N1 revealed a main effect of Alerting, with more negative amplitudes for double-cue (-2.28 μV; SE: 0.51) than for no-cue trials (-1.43 μV; SE: 0.39; $F(1,63) = 11.42$, $MSe =$ 55.96, $p < .001$, $\eta_p^2 = 0.154$). No other main or interaction effects reached significance (all F's < 2.71).

Target-P3 (350–550 ms after target). Target-P3 demonstrated a main effect of Alerting, with greater positive amplitudes for no-cue (6.67 μV; SE: 0.47) than for double-cue trials (5.68 μV; SE: 0.40; $F(1,63) = 31.36$, $MSe = 27.85$, $p < .001$, $\eta_p^2 = 0.332$). There was also a main effect of Context ($F(2,126) = 5.53$, $MSe = 26.48$, $p < .01$, $\eta_p^2 = 0.081$). There was no main effect of Experiment ($F < 1$); however, Experiment and Context showed an interaction for the single mixed contrast ($F(2,63) = 9.03$, $MSe = 21.23$, $p < .005$, $\eta_p^2 = 0.125$) but not for the contrast between the two single conditions ($F < 1$). No other effects were significant (all F's $<$ 1.63).

The two-way interaction between Experiment and Context revealed an effect of single context versus mixed context in both the bilingual experiment and the word-type experiment (respectively, $F(1,22) = 7.44$, $MSe = 23.18$, $p < .05$, $\eta_p^2 = 0.253$ and $F(1,20) = 7.42$, $MSe = 20.76$, $p <$ $.05$, $\eta_p^2 = 0.271$), but not in the color experiment ($F < 1$). The Context effect in the bilingual and word-type experiment was reflected in greater positive amplitudes in the mixed (respectively, 6.37 μV; SE: 0.58 and 7.16 μV; SE: 0.75) than in the single context (respectively, 5.45 μV; SE: 0.58 and 6.26 μV; SE: 0.90).

3.2.2. *Orienting network*

The analysis consisted of the same within-subjects factors Orienting (central cue vs. spatial cue) and Context (single1 vs. single2 vs. mixed), as well as the between-subjects factor Experiment (bilingual, color, vs. word type) throughout the parietal region (pooled over CP1, CPz, CP2, P1, Pz, P2, O1, Oz, O2). See Fig. 3 for the Context effect.

Target-N1 (180–220 ms after target). Target-N1 revealed a main effect

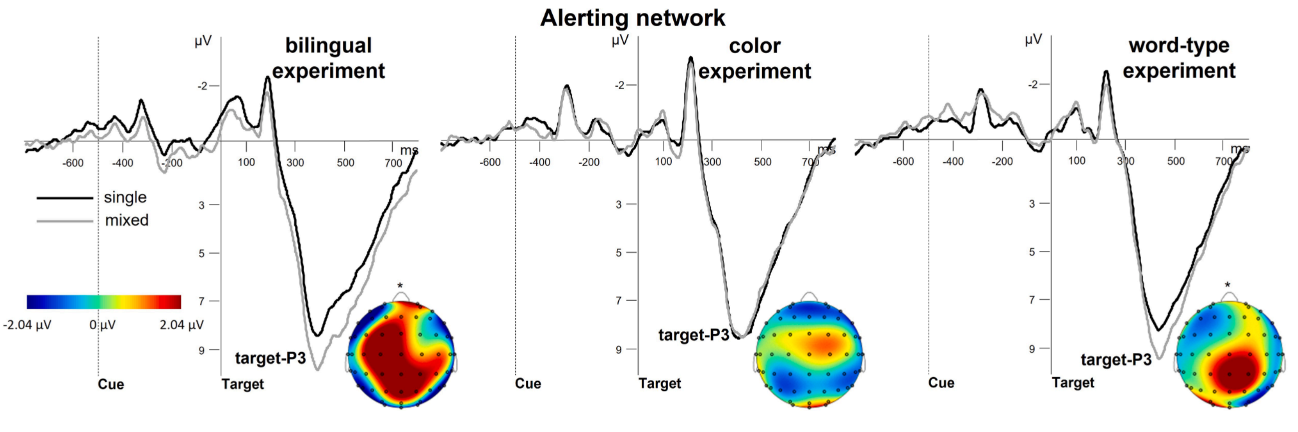

Fig. 2. Averaged stimulus-locked ERP waveforms for the parietal region (pooled over CP1, CPz, CP2, P1, Pz, P2, O1, Oz, O2), showing the single (black line) and mixed contexts (grey line) for the **alerting network** in the three Experiments (Experiment 1: bilingual; Experiment 2: color; Experiment 3: word type). A 25 Hz filter was applied to improve the clarity of the waveforms in the figures. For the target-P3 component, topographical maps are presented with the difference waves between contexts (single vs. mixed). The asterisks above some maps indicate significant effects for context.

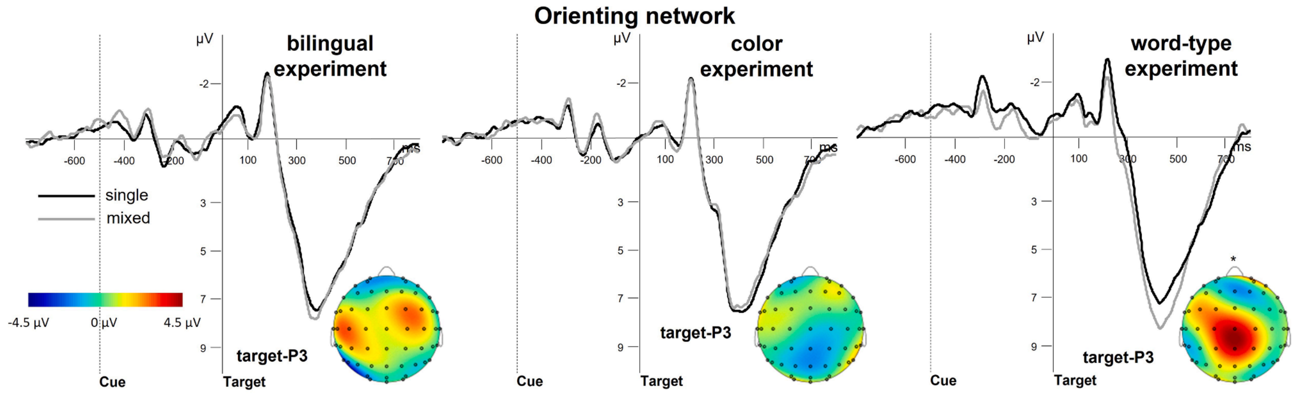

Fig. 3. Averaged stimulus-locked ERP waveforms for the parietal region (pooled over CP1, CPz, CP2, P1, Pz, P2, O1, Oz, O2), showing the single (black line) and mixed contexts (grey line) for the **orienting network** in the three Experiments (Experiment 1: bilingual; Experiment 2: color; Experiment 3: word type). A 25 Hz filter was applied to improve the clarity of the waveforms in the figures. For the target-P3 component, topographical maps are presented with the difference waves between contexts (single vs. mixed). The asterisks above some maps indicate significant effects for context.

of Orienting, with more negative amplitudes for spatial-cue (-1.90 μV; SE: 0.46) than for no-cue trials (-1.31 μV; SE: 0.45; $F(1,63) = 11.49$, $MSe = 27.23$, $p < .001$, $\eta_p^2 = 0.154$). No other main or interaction effects reached significance (all *F's* < 1.20).

Target-P3 (350–550 ms after target). Target-P3 demonstrated a main effect of Orienting ($F(1,63) = 49.48$, $MSe = 55.73$, $p < .001$, $\eta_p^2 = 0.440$), with greater positive amplitudes for the central (6.90 μV; SE: 0.46) than for the spatial-cue trials (5.14 μV; SE: 0.40). No other main effects reached significance (all *F's* < 1.46). Furthermore, the interaction between Experiment and Context (single versus mixed contrast) was significant ($F(2,63) = 3.74$, $MSe = 21.44$, $p < .05$, $\eta_p^2 = 0.106$), but not for the contrast between the two single conditions ($F < 1$). No other interaction effects were significant (all *F's* < 2.07).

The two-way interaction between Experiment and Context revealed an effect of single context versus mixed context in the word-type experiment ($F(1,20) = 8.33$, $MSe = 23.01$, $p < .01$, $\eta_p^2 = 0.294$), but not in the bilingual experiment and color experiment (*F's* < 1). The Context effect in the word-type experiment was reflected in greater positive amplitudes in the mixed context (7.12 μV; SE: 0.81) than in the single context (6.11 μV; SE: 0.87).

3.2.3. Executive control network

The analysis consisted of the within-subjects factors Congruency (congruent vs. incongruent), Context (single1 vs. single2 vs. mixed), and Experiment (bilingual, color, vs. word type) throughout the central region (pooled over 20 electrodes: FC3, FC1, FCz, FC2, FC4, C3, C1, Cz, C2, C4, CP3, CP1, CPz, CP2, CP4, P3, P1, Pz, P2, P4). See Fig. 4 for the P3 components of the Executive control network.

Target-P3 (300–500 ms after target). The target-P3 component amplitude showed a main effect of Congruency with greater positive amplitudes for congruent (5.53 μV; SE: 0.44) than for incongruent trials (4.63 μV; SE: 0.44; $F(1,63) = 26.42$, $MSe = 60.73$, $p < .001$, $\eta_p^2 = 0.295$). There was also a main effect of Context ($F(2,126) = 4.22$, $MSe = 52.25$, $p < .05$, $\eta_p^2 = 0.063$). Single versus mixed contexts interacted with Experiment ($F(2,63) = 3.76$, $MSe = 71.94$, $p < .05$, $\eta_p^2 = 0.123$). As expected, the two single-language contexts did not interact with Experiment ($F < 1$). No other effects reached significance (all *F's* < 1.81).

The two-way interaction between Experiment and Context revealed an effect of single context and mixed context in both the bilingual experiment and the word-type experiment (respectively, $F(1,22) = 7.08$, $MSe = 70.03$, $p = .05$, $\eta_p^2 = 0.244$ and $F(1,20) = 8.08$, $MSe = 81.34$, $p = .01$, $\eta_p^2 = 0.288$), but not in the color experiment ($F < 1$). The Context effect in the bilingual and word-type experiment was reflected in greater positive amplitudes in the mixed context (respectively, 5.28 μV; SE: 0.62 and 6.17 μV; SE: 0.95) than in the single context (respectively, 4.54 μV; SE: 0.62 and 5.29 μV; SE: 1.03).

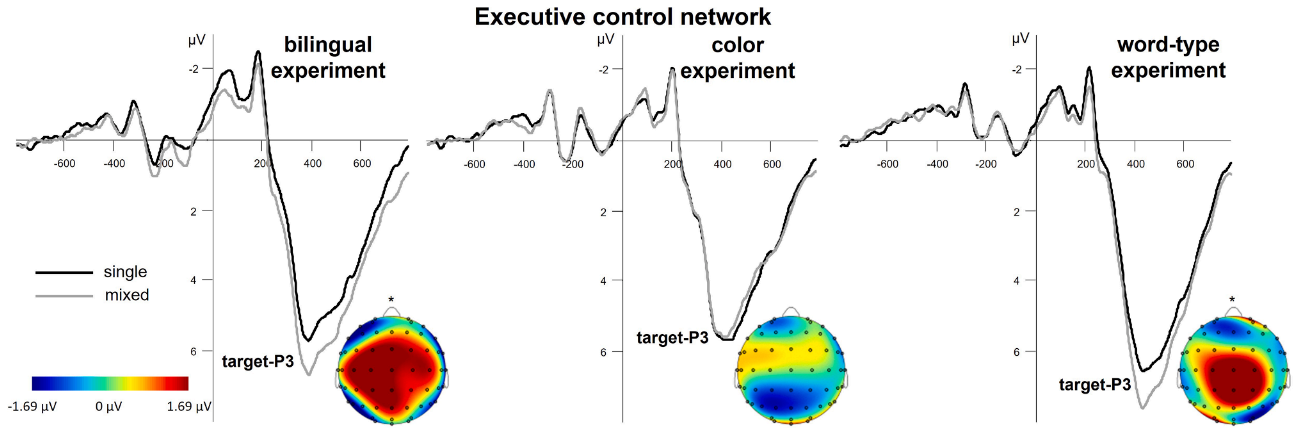

Fig. 4. Averaged stimulus-locked ERP waveforms for the central region (pooled over FC3, FC1, FCz, FC2, FC4, C3, C1, Cz, C2, C4, CP3, CP1, CPz, CP2, CP4, P3, P1, Pz, P2, P4), showing the single (black line) and mixed contexts (grey line) for the **executive control** network in the three Experiments (Experiment 1: bilingual; Experiment 2: color; Experiment 3: word type). A 25 Hz filter was applied to improve the clarity of the waveforms in the figures. For the target-P3 component, topographical maps are presented with the difference waves between contexts (single vs. mixed). The asterisks above some maps indicate significant effects for context.

3.2.4. Assessing the impact of mixed context

For the alerting network, alerting cues had a facilitated effect compared to no cues in the target-N1 component. Similarly, language switches compared to language repetitions had a facilitating effect in the target-N1 component (Timmer et al., 2021; Experiment 1). Therefore, we attempted to determine whether other types of switches enhance processing of upcoming information in the same way as alerting and language switches, as indexed by target-N1. The within-subjects factor Switching (switch vs. repeat) was analyzed in each Experiment (bilingual, color, vs. word type) throughout the parietal region (pooled over CP1, CPz, CP2, P1, Pz, P2, O1, Oz, O2). See Fig. 5 for the Switching effect.

Target-N1 (160-200 after target). For the bilingual experiment, there was a main effect of Switching, with greater negative amplitudes after language-switch trials (-2.43 μV; SE: 0.83) than after language-repeat trials (-1.81 μV; SE: 0.81; $F(1,22) = 4.87$, $MSe = 16.59$, $p < .05$, $\eta_p^2 = 0.181$); this was very similar to the alerting effect. However, neither the color experiment ($F < 1$) nor the word-type experiment showed a switching effect ($F(1,20) = 1.43$, $MSe = 11.36$, *ns*).

4. Discussion

In the last decade, an increasing number of studies have shown that a bilingual language context, compared to a monolingual context, enhances the efficiency of domain-general mechanisms (Jiao et al., 2019; Timmer, Calabria, & Costa, 2019; Timmer et al., 2021; Wu & Thierry, 2013; Yang, Ye, Wang, Zhou, & Wu, 2018; for a review see Wodniecka et al., 2020). However, which exact sub-mechanism is modulated by language contexts is still a matter of debate. Within the flanker task (i.e., the executive control network), some studies have argued that enhancement occurs during *conflict resolution* (Wu & Thierry, 2013; Yang et al., 2018), while others have argued that enhancement occurs during *conflict monitoring* (Jiao et al., 2019). To understand the reason behind these inconsistent findings, in Timmer, Wodniecka, and Costa (2021) we extended our exploration beyond the impact of bilingual context on the executive control network to a possible impact on the alerting network. The results of that investigation (also briefly reported here as Experiment 1) suggest that the processing locus of adaptations occurs before conflict resolution.

To understand better what exactly underlies the adaptation process in a bilingual language context and translates into the observed increase in attentional efficiency, we followed up on our previous findings (Experiment 1) and investigated two different types of single- and mixed-language contexts in the current study. One context was related to low-level variability in the perceptual environment (mixing of words written in blue or red ink in Experiment 2) and another context was related to higher-order switching processes (mixing nouns and verbs in Experiment 3). In a direct comparison with Experiment 1, we found that mixing word types (nouns and verbs) revealed enhancement of attention in the executive control and alerting networks, as indexed by greater target-P3 amplitudes that were comparable to the previously observed enhancement in the bilingual language context of Experiment 1. Importantly, no such enhancement was observed when the mixed context involved mixing only the lower-level features of stimuli, (i.e., ink color). Thus, it seems that any mixed context in which switches between categories are related to semantic features (i.e., meaning of the words) can enhance attentional capacity in a similar way as a bilingual context does. This suggests that an environment in which some aspects of a language system change dynamically tunes the attentional system and its underlying neural mechanism. Below, we discuss the reported effects' possible origin and the implications for theories of bilingual language control.

4.1. The origin of attention modulations due to mixed contexts

Support for the claim that the origin of bilingual context modulations is related to general monitoring (Jiao et al., 2019; Timmer et al., 2021) comes from data obtained in Experiment 3. This experiment demonstrated that a context that included mixed linguistic categories (nouns and verbs) enhanced activation of target-P3 in the executive control and alerting networks. This influence was similar to the bilingual language context in Experiment 1. The overall enhancement of target-P3 amplitudes in the executive control network suggests that this enhancement in mixed contexts is in *conflict monitoring* rather than in *conflict resolution*. The overall enhancement of target-P3 amplitudes in the alerting network suggests that the attentional effect could also occur at a more general attentional level (i.e., *state of alertness*). This because the target-P3 in the alerting network (no cue vs alerting cue) reflects not conflict

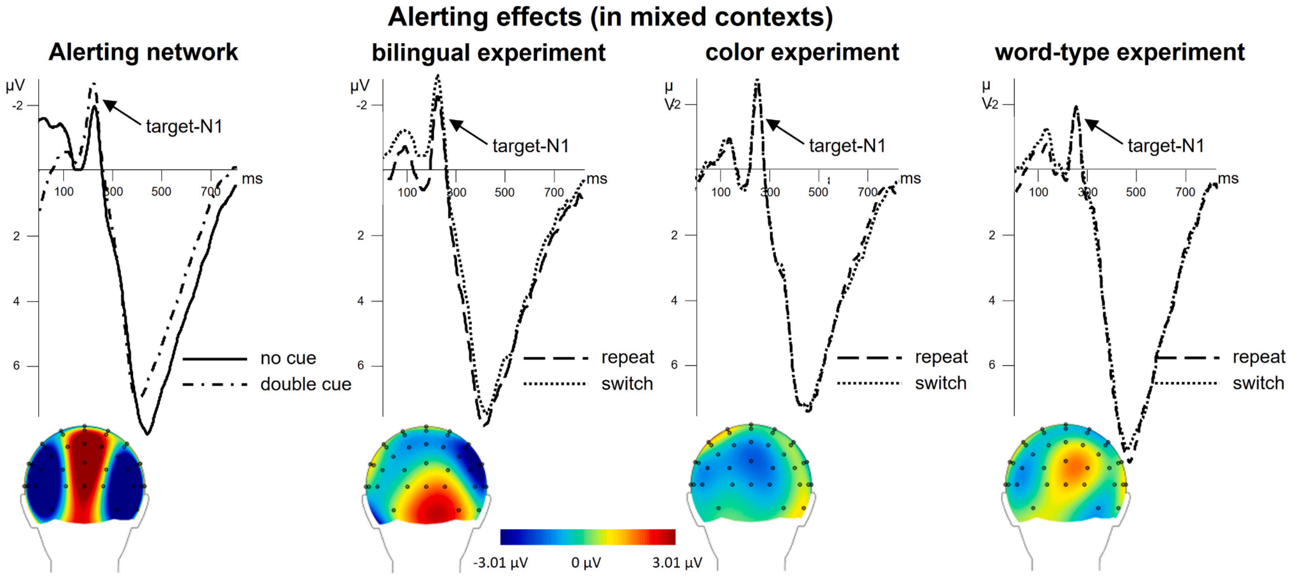

Fig. 5. Averaged stimulus-locked ERP waveforms for the parietal region (pooled over CP1, CPz, CP2, P1, Pz, P2, O1, Oz, O2) were baselined between −600 and −500 before the target (i.e., flanker) presentation (0 ms). The comparison between the alerting network and the mixed contexts is only visual in nature. For the alerting network, the no-cue (solid line) and double-cue (dashed-dotted line) trials are presented. For the switching effect, repeated language trials (long dashed line) and switched language trials (short, dashed lines) are presented for each experiment. A 25 Hz filter was applied to improve the clarity of the waveforms in the figures.

monitoring but alerting during target detection (Timmer et al., 2021). Because both mixed contexts from Experiment 1 and 3 enhanced domain-general attentional processes in ANT, we suggest that both types of adaptations are handled by an early common mechanism of attentional control. In turn, this can lead to enhancement of later conflict resolution, as found in the seminal study by Wu and Thierry (2013).

While attentional processing was enhanced in the mixed linguistic category (nouns vs verbs) context, it was not in the mixed color contexts (red vs blue). This suggests that it is not low-level perceptual variability that accounts for the attentional enhancement observed in Experiment 1, in which we placed participants in monolingual and bilingual contexts. As mentioned in the Introduction, one could argue that perceptually salient, orthographic differences between languages (e.g., -d ending in Spanish or -t ending in Catalan) could drive the observed attentional adaptations. We believe that the results of Experiment 2 speak against the idea that mixed-context modulations originate from low-level perceptual changes (e.g., color or letter changes). Instead, based on the results of Experiment 3, we propose that the attentional adaptation observed in the bilingual context concerns implicit (language or semantic) categorization, which requires deeper processing and higher-order processing. We suggest that this implicit process of switching on a lexical-semantic level activates (and enhances) the state of alertness and the monitoring system. However, the implicit process of switching between perceptual differences in the two languages does not activate the attentional system. To conclude, a bilingual experience consists of a complex set of factors that dynamically impact attentional processing. However, different monolingual experiences can lead to similar dynamic adaptations of the attentional system. Therefore, the observed attentional enhancement is not specific to language switching in a bilingual context but is intrinsic to other linguistic between-categories contexts (verbs and nouns), at least in bilinguals. An important next step is exploring the scope of these short-term between-category modulations in monolinguals.

The idea that the state of alertness was enhanced in bilingual contexts is supported by the finding that language switches, compared to language repetition trials, increased target-N1 amplitudes (see Fig. 5). As demonstrated in previous studies, arbitrary cues enhance target N-1, which can be interpreted as heightened processing of upcoming stimuli (Asanowicz, Wołoszyn, Panek, & Wronka, 2019; Böckler, Alpay, & Stürmer, 2010; Jepma, Wagenmakers, Band, & Nieuwenhuis, 2009; Neuhaus et al., 2010). Interestingly, in our study, while language switches (Experiment 1) showed an alerting function through target-N1 modulations, this same effect was not present for within-language between-category switches (Experiment 3). In other words, the alerting effect seems to be strong when there is a change of languages in the environment, thus there is a need to activate a different language system for communication. When there is a change of word type but the language stays the same, activation of the alerting system seems to be weaker. This seems to make perfect sense as we intermix different word types in sentences but typically stick to the same language, especially when reading (i.e., most written texts do not use code-switching). Additionally, switching between nouns and verbs within the same language (Experiment 3) enhanced not only the alerting network but also the orienting network. This effect was surprising, although it can be argued that typical reading requires spatial attention to move from the beginning to the end of a text. This might be the reason for the enhanced orienting that only occurred during the word-type experiment. However, the origin of this effect is unclear at this point, so further research is needed to expand our understanding of this effect. Overall, the obtained effects show that a context with multiple languages or different types of word categories within the same language show some similarities but also some differences.

Further evidence for the domain-general nature of language monitoring comes from outside of the current study, i.e., from research on self-monitoring in speech production. These studies showed that self-monitoring of one's verbal performance (i.e., detecting whether you make an error while naming pictures) activates the Error Related Negativity (ERN) component, which is suggested to originate in the Anterior Cingulate Cortex (ACC) (Acheson et al., 2012; Ganushchak & Schiller, 2006, 2008; Riès et al., 2011). This component and area do not only respond to errors but are also activated during correct responses in the presence of conflict, like naming words in the presence of similar distractor words (De Zubicaray, McMahon, Eastburn, & Wilson, 2002), naming cognates (Acheson et al., 2012), and the flanker and Stroop tasks (Botvinick, Carter, Braver, Barch, & Cohen, 2001). These findings are interpreted as the engagement of a monitoring system during response conflict across language and domain-general modalities (Acheson et al., 2012). Botvinick et al., (2001) propose that the demand for control during (among others) the flanker task may in part be dealt with by conflict monitoring. The idea that the same monitoring system is activated during processing of information in various domains has also been demonstrated in studies comparing verbal with non-verbal monitoring tasks (Ambrosini et al., 2019, 2020). The domain-general nature of the effects has been at the core of the hypothesis that bilinguals may benefit in domain-general control processes due to lifelong training in language switching. Bilinguals, compared to monolinguals, showed more overlap in the N2 and P3 components between the linguistic and non-linguistic switching paradigms. This suggests domain generality for control processes (Timmer, Grundy, & Bialystok, 2017a). Whether we talk about early attentional processes (i.e., state of alertness), conflict monitoring, or conflict resolution, they all extend to domain-general processing.

4.2. *Dissociations between neural and behavioral data*

The present experiments showed that different mixed linguistic contexts may create a state of alertness that prepares the system for possible upcoming changes on the neural level in the absence of behavioral performance differences. The dissociation between behavioral and electrophysiological measures is commonly reported in the literature because no single ERP component determines the final response speed (Huster, Messel, Thunberg, & Raud, 2020; Timmer & Chen, 2017; Timmer, Vahid-Gharavi, & Schiller, 2012; Wodniecka, Szewczyk, Kałamała, Mandera, & Durlik, 2020). The reason that we found modulations of ERPs between different language contexts in the absence of such behavioral modulations could be because the target-P3 targets the specific mechanisms of higher-order attentional control, while behavioral effects are the end-product of multiple sub-mechanisms. Another reason for the absence of a behavioral impact of context in the present experiments is that the words that created the contexts were presented 3 s before the target flanker. Cues (e.g., words, asterisks) have a stronger alerting effect when they are presented less time before the target (e.g., flanker), as was the case for arbitrary alerting cues presented 500 ms before the flanker. Therefore, the behavioral impact of mixed contexts might have been diminished by the effects of the alerting cue.

4.3. *Theoretical implications*

The reported effects in the present study support the proposal that the process during which enhancement occurs is earlier than previously assumed. We suggest this enhancement is not related to inhibition of words from the unintended language during bilingual language production (as suggested previously, e.g., in Timmer, Grundy, & Bialystok, 2017a; Wu & Thierry, 2013). Instead, we propose that the locus of adaptations/enhancement occurs during monitoring of the language context for possible upcoming changes of languages, which is crucial to achieve effective communication (Costa et al., 2009), and during the earlier and more general attentional process of alerting. This idea is supported by work with translators which suggests that language control is mediated through attentional processes such as monitoring (Dong & Li, 2020).

The findings that the attentional adaptations observed in the bilingual context originate from language monitoring (Experiment 1) and that similar effects can be found under some mixed contexts even within a single language (Experiment 3) have important implications for theorizing on the nature of bilingual language control. They inform the main model of Inhibitory Control (IC) by Green (1998) that has inspired much of the research on the cognitive consequences of bilingualism and directed the focus to the inhibitory processes. The IC model suggests that the main locus of control during these tasks is in the lexico-semantic system (in which words from both languages are stored) and in language task schemas (which alter the activation levels of a language as a whole). These processes are crucial for outputting the intended language while inhibiting the unintended language. These control mechanisms are suggested to be mediated by the Supervisory Attentional System (SAS) when a novel task must be performed for which no schema is yet constructed, or when existing schemas have to be altered. Based on the outcomes of the studies presented in this paper, we suggest that SAS, which monitors performance during, among others, switching between non-linguistic tasks (Norman & Shallice, 1986), is activated directly by context switches on every single trial. We propose the relation between Bilingual Language Control (BLC) and Executive Control (EC) is mediated by attentional processes (SAS), which occur before the original locus of BLC (i.e., inhibitory control in the IC model, Green, 1998). Within the context of bilingual language use, SAS is therefore not only important for regulating language changes; it is also responsible for changing between tasks that do not involve language. Because not only the bilingual language context but also the noun–verb mixed context impacted domain-general attentional processes in ANT, we suggest that all these abilities are handled by an early common mechanism of attentional control in SAS. In turn, as part of the conflict has already been resolved during conflict monitoring, this can reduce the need for later control processes.

Although some previous studies support the assumption that the origin of attentional modulations across domains occurs during conflict monitoring (Acheson et al., 2012; Botvinick et al., 2001; Costa et al., 2008; Marzecová, Bukowski, et al., 2013), future research is warranted to understand the role of alerting even better. In Timmer et al., (2021) we argue that bilingual experiences involve a complex network of processes that start with exposure to a multitude of external cues, such as the presence of familiar or socio-cultural faces (Blanco-Elorrieta & Pylkkänen, 2017; C. Liu, Timmer, Jiao, Yuan, & Wang, 2019) and the presence of the languages themselves (Grosjean, 2001; Timmer et al., 2017b). During language switching, these cues reduce the need for control processes. In Timmer et al., (2021), we argue that these cues in our environment enhance the state of alertness during bilingual and other mixed contexts. Therefore, the demand for control during language switching and domain-general switching may not only be dealt with in part by conflict monitoring (Botvinick et al., 2001) but also by alerting.

A final important note is that the modulations in the present study occurred while passively perceiving switches between languages. This suggests not only experiences in active production of different languages, but also passive exposure to different languages can modulate domain-general attentional efficiency. This also raises the question of whether monolinguals that are frequently exposed to other languages and have only rudimentary knowledge of these languages will also show such adaptations.

To conclude, the present study shows that when bilinguals change between some aspects of linguistic environments (e.g., switching between languages or switching between categories within one language), the efficiency of the domain-general attention system gets dynamically enhanced. This short-term neuroplasticity can impact bilinguals in the longer run.

CRediT authorship contribution statement

Kalinka Timmer: Conceptualization, Methodology, Investigation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing, Funding acquisition. **Albert Costa:** Conceptualization, Funding acquisition. **Zofia Wodniecka:** Conceptualization, Writing – review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Ethics statement

The study was approved by the ethical committee board at Universitat Pompeu Fabra. All participants were adults aged 18 or more. At the beginning of the experimental session participants signed an informed consent form that stated a description of the experiment and stressed that the participant is free to leave the experiment at any time without providing any explanation to the experimenter. If the participant wants to proceed, they sign the consent form, and the experiment commences.

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