Perceptual Decoupling Underlies Internal Shielding Benefit during Switches between External and Internal Attention: Evidence from Early Sensory Event-related Potential Components

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Abstract

■ People need to often switch attention between external and internal sources of information, that is, external and internal attention, respectively. There has been a recent surge of research interest in this type of attentional flexibility, which has revealed that it is characterized by an asymmetrical cost, being larger for switching toward internal than external attention. This cost asymmetry has been explained in terms of an internal shielding benefit, that is, the maintenance of stable internal attention against external interference. Although it is currently unclear how internal information might be shielded from external input during switches, a likely candidate is perceptual decoupling. In this study, we instructed participants to repeat external or internal attention, or to switch between them from trial to trial, while simultaneously recording 64-channel EEG. At the behavioral level, we replicated the switch cost asymmetry. Our ERP analysis provided evidence for three different processing stages. First, participants prepared more strongly for an upcoming internal than external attentional selection, as reflected in the increased contingent negative variation component. Second, during internal trials, participants moreover showed a blunted sensory response, most notable in the P1 and N1 components, reflecting perceptual decoupling. Finally, we found an increased P2 component when switching toward internal attention compared with repeating it, indicating more stable perceptual decoupling on internal repetition trials, in line with an internal shielding benefit. We integrate these findings here with behavioral accounts of the cost asymmetry and conclude that perceptual decoupling provides a potential mechanism for the internal shielding benefit of attention. ■

INTRODUCTION

Attention is the selective prioritization of a subset of information from current external (sensory) or internal (mental) input, at the cost of unattended information (Chun, Golomb, & Turk-Browne, 2011). For example, external attention allows one to focus on reading this paragraph instead of attending to colleagues having a conversation in the background, whereas internal attention makes it possible to think about dinner plans for this evening while not getting distracted by another thought, such as a memory of a previous dinner. In addition to this selection within external and internal attention, attentional selection also needs to take place between them (Narhi-Martinez, Dube, & Golomb, 2023; Verschooren, Schindler, De Raedt, & Pourtois, 2019). Returning to our example, if while reading this paragraph attention is diverted to your dinner plans instead, you will notice that only one of the two can be prioritized for central processing at any one time (or placed in the focus of attention). This bottleneck likely stems from overlapping selection mechanisms for external and internal attention, especially at later stages of processing (Verschooren & Egner, 2023; Zhou, Curtis, Sreenivasan, & Fougnie, 2022; Panichello & Buschman, 2021, for a review). An important implication is that, in this common situation, attention has to switch between external and internal sources of information to align with our current goals (Servais, Hurter, & Barbeau, 2023; Tarder-Stoll, Jayakumar, Dimsdale-Zucker, Günseli, & Aly, 2020; Verschooren, Schindler, et al., 2019; Honey, Newman, & Schapiro, 2017). Although initial research into this topic started at the end of last century (e.g., Carlson, Wenger, & Sullivan, 1993; Dark, 1990; Weber, Burt, & Noll, 1986), there has recently emerged a renewed interest in switches between external and internal attention (e.g., Gresch, Boettcher, Gohil, van Ede, & Nobre, 2024; Gresch, Boettcher, van Ede, & Nobre, 2024; Wang, Verschooren, Vermeylen, Grahek, & Pourtois, 2024; Hautekiet, Verschooren, Langerock, & Vergauwe, 2023; Poskanzer & Aly, 2023; Weilnhammer, Stuke, Standvoss, & Sterzer, 2023; Calzolari, Boneva, & Fernández-Espejo, 2022; Verschooren, Pourtois, & Egner, 2020; Verschooren, Liefooghe, Brass, & Pourtois, 2019; Burgess, Dumontheil,

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& Gilbert, 2007; Gilbert, Frith, & Burgess, 2005). A consistent finding, independent of the specific tasks or stimuli used, is that such switches are associated with a processing cost, indicating the presence of an attentional bottleneck. Moreover, research with the switching attention task (SAT; Wang et al., 2024; Hautekiet et al., 2023; Verschooren et al., 2020; Verschooren, Liefooghe, et al., 2019) has provided robust evidence that this cost is larger when switching attention from external to internal input than the other way around (see also Gresch, Boettcher, van Ede, et al., 2024; Calzolari et al., 2022; Dark, 1990). It has been proposed that this cost asymmetry derives from an internal shielding benefit (Verschooren & Egner, 2023; Verschooren et al., 2020), but this proposal is based on mostly indirect evidence from behavioral findings. Interestingly, in the context of mind wandering, researchers have suggested that a form of internal shielding occurs when participants engage with internal thought, through a process called perceptual decoupling (e.g., Smallwood & Schooler, 2006, 2014; Kam & Handy, 2013). Such perceptual decoupling can, for example, be observed in the amplitude of early sensory ERP components, such as the P1 and N1 (Kam, Mittner, & Knight, 2022). Given that mind wandering is a form of spontaneous internal attention, with several similarities to selective internal attention as defined here (Verschooren & Egner, 2023; see also Mittner, Hawkins, Boekel, & Forstmann, 2016), the question arises whether perceptual decoupling occurs during switches toward internal attention as well and can underlie the internal shielding benefit. To address this open question, we collected 64-channel scalp EEG while participants switched between external and internal attention on a trial-by-trial basis, which allowed us to shed light on the bottleneck of attention switches and the presence of perceptual decoupling.

In a previous study based on a different paradigm than the SAT, we recorded a 64-channel EEG while participants occasionally switched attention either from one external to another external task, or from an internal to an external task (Verschooren, Schindler, De Raedt, & Pourtois, 2021). The external (baseline) task was the same in both conditions, which isolated the effects of a switch between attention domains (internal-to-external) and within attention domain (external-to-external). This study examined ERPs generated in response to the (visual) cue indicating a switch back to the baseline external task. Results showed that the visual extrastriate P1 component was decreased as a result of this switch, and that this reduction was more pronounced for a switch from internal to external attention. These results provided neurophysiological evidence for the presence of a bottleneck and the sharing of selection mechanisms between internal and external attention during such switches (Verschooren, Schindler, et al., 2021). Moreover, these ERP results suggested that early on following cue onset in extrastriate visual cortex, information processing is gated depending on the direction of this switch. However, a main limitation of that previous ERP study was that it did not inform about the switch cost asymmetry discussed here above, which seems to be a key characteristic of this type of attentional flexibility. That is, this previous experimental design only compared infrequent switches of attention from external to internal modalities versus between two external ones, but did not cover the other directions. As a result, to date, we have only a partial understanding of attentional flexibility at the neurophysiological level.

The SAT provides several methodological improvements compared with this earlier task, as both directions of attention switches can be investigated with it (Wang et al., 2024; Hautekiet et al., 2023; Verschooren et al., 2020; Verschooren, Liefooghe, et al., 2019). In the SAT, attention switches from the external to the internal domain and vice versa occur with an equal probability, while keeping the (visual probe-matching) task constant across them (Verschooren, Liefooghe, et al., 2019). Specifically, participants are instructed to complete a target-to-probe matching task in which the targets are either presented on screen (external trial) or retrieved from memory (internal trial) on a trial-by-trial basis. By comparing different trial transitions, four conditions can be distilled that cover all possible transitions between external and internal attention: external-repetition, external-switch, internal-repetition, and internal-switch (see Figure 1). That is, the conditions are defined by considering the current trial (n) and the previous one ($n - 1$), that is, an external trial preceded by an external one (external-repetition) versus an internal one (external-switch) or an internal trial preceded by an internal one (internal-repetition) versus an external one (internal-switch). When comparing the differences between switch and repetition trials for external and internal trials separately, a larger cost for switching to internal (i.e., the difference between internal-switch and internal-repetition) than vice versa (i.e., the difference between external-switch and external-repetition) has consistently been observed at the behavioral level (Wang et al., 2024; Hautekiet et al., 2023; Verschooren et al., 2020; Verschooren, Liefooghe, et al., 2019).

Asymmetrical switch costs have often been observed when switching between a dominant and nondominant task, with the dominant task showing a larger switch cost (e.g., Mayr, Kuhns, & Hubbard, 2014; Yeung & Monsell, 2003a, 2003b). Applied to switches between external and internal attention, this raises the interesting possibility that internal attention is in fact dominant over external attention (Verschooren & Egner, 2023; Verschooren et al., 2020). To determine whether this is the case, Verschooren and colleagues (2020) directly tested the predictions from three rival accounts, that is, priming (e.g., Yeung & Monsell, 2003a, 2003b; Gilbert & Shallice, 2002; Allport, Styles, & Hsieh, 1994), associative interference (e.g., Mayr et al., 2014; Waszak, Hommel, & Allport, 2003), and memory retrieval (e.g., Dark, 1990). The results fit best with the predictions from the associative interference account,

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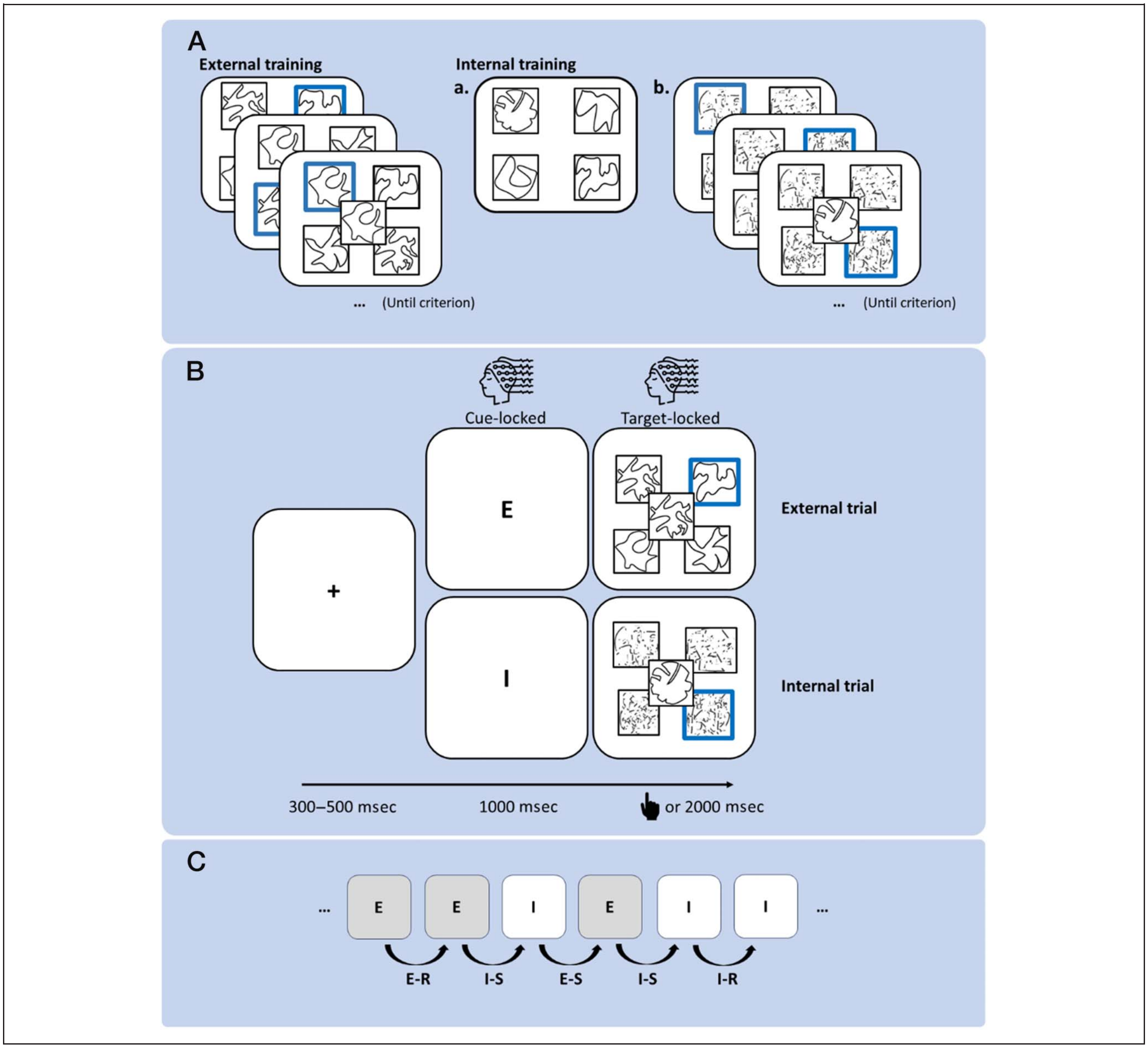

Figure 1. SAT. (A) Participants completed an external and internal training phase. In the external training phase, they had to respond whether the centrally presented probe matched the target (in blue). (Aa) In the internal training phase, they first memorized four stimuli and their location (self-paced). (Ab) Participants then responded whether the probe matched the target memorized in the selected location (in blue). Both phases were continued until an accuracy criterion was reached. (B) Each trial started with a jittered interval (300–500 msec), followed by the presentation of the cue ("E" and "I" for external and internal trials, respectively) for 1000 msec, after which the targets appeared on screen until response or for 200 msec. (C) External and internal trials followed each other (pseudo)randomly, creating the four conditions of interest: external-repetition (E-R), external-switch (E-S), internal-repetition (I-R), and internal-switch (I-S).

which indeed implies internal dominance. Generally speaking, this account assumes that when switching between tasks, participants associate the stimuli with both competing task sets, which can lead to interference (e.g., Mayr et al., 2014; Waszak et al., 2003; for reviews, see Vandierendonck, Liefooghe, & Verbruggen, 2010; Monsell, 2003). Such an association can similarly be formed with the higher-order attentional settings required to carry out the task and efficiently deal with the demands imposed by the current task context (see also Braem & Egner, 2018; Chiu & Egner, 2017; Abrahamse, Braem, Notebaert, & Verguts, 2016), for example, an external versus an internal focus of attention.

In the context of the SAT, the associative learning account implies that traces of both external and internal attentional settings are activated and compete throughout the task. A processing cost occurs when switching between external and internal attention because a (procedural) working-memory update is required, which leaves attention especially vulnerable to interference from the

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irrelevant attentional settings (see also Verschooren, Kessler, et al., 2021). When applied to the observed cost asymmetry, the larger switch cost for internal attention is explained by assuming that, on repetition trials, the dominant internal attentional set can be shielded efficiently from external attentional interference. On switch trials, however, strong interference occurs for both nondominant and dominant attentional sets equally, as the required working memory update renders attentional shielding ineffective. This results in a large difference between repetition and switch trials for internal trials. The small switch cost on external trials, on the other hand, is due to inefficient shielding of external attention on external repetition trials, leading to a significant amount of internal interference on these trials, and a small difference between those trials and switch trials. As such, the finding that this associative learning account explains the data best, implies that participants shield their attention more effectively on internal trials than on external ones, that is, an internal shielding benefit (Verschooren, Pourtois, et al., 2020). In other words, although it is difficult to shield against irrelevant information previously learned within a similar task context, novel irrelevant information can be shielded against under certain circumstances. Interestingly, this interpretation implies that the cost asymmetry cannot easily be explained in terms of a difficulty account, despite participants being slower and more error prone on internal trials (see Verschooren & Egner, 2023, for detailed arguments).

Further supporting this internal shielding benefit, a recent study found that during hypervigilance, which is a state characterized by an artificially increased focus on the external environment, the cost asymmetry disappeared (Wang et al., 2024). Behavioral modeling further revealed that this reduced cost asymmetry was caused by slower evidence accumulation on internal trials, indicative of reduced shielding of internal attention. More broadly, Verschooren and Egner (2023) extended this internal shielding account to other literatures speaking to the balance of external and internal attention, such as working memory and visual search (e.g., Olivers, Peters, Houtkamp, & Roelfsema, 2011; Soto, Hodsoll, Rotshtein, & Humphreys, 2008), sustained attention (e.g., Esterman & Rothlein, 2019; Thomson, Besner, & Smilek, 2015), mind wandering (e.g., Mittner et al., 2016; Killingsworth & Gilbert, 2010), and meditation (e.g., Laukkonen & Slagter, 2021). They concluded that an internal shielding benefit of attention can account for disparate findings in these research domains.

However, based on the existing behavioral findings alone, it is difficult to determine what mechanism might underlie such an internal shielding benefit. One likely candidate is perceptual decoupling, which is a neural process originally proposed in the context of mind-wandering research. Mind wandering is an umbrella term for a diverse range of internal cognitive processes that can be described as task-unrelated and directed toward a self-generated thought (Seli et al., 2018). Research in the field of mind wandering has shown that the brain is less responsive to external stimuli during episodes of mind wandering, when attention is directed internally to self-generated thoughts. This perceptual decoupling process is evident in a blunted response to external, sensory input, as, for example, reflected in the amplitude of the early visual P1 and N1 components (e.g., Smallwood, 2013; Schooler et al., 2011; Smallwood & Schooler, 2006; see Kam et al., 2022; Kam & Handy, 2013, for reviews). Interestingly, although the primary sensory cortices show a reduced activation, the secondary visual and somatosensory cortices remain nonetheless responsive (e.g., Wheeler, Petersen, & Buckner, 2000). As such, internal input can be processed in the secondary visual and somatosensory cortices and used to guide behavior without interference from simultaneous information coming from primary sensory cortices. Although this process is well established in the mind-wandering literature, the evidence for other forms of internal attention remains scant (see Servais et al., 2023, for a recent review; see also Korda, Walcher, Körner, & Benedek, 2023; Benedek, Stoiser, Walcher, & Körner, 2017; Walcher, Körner, & Benedek, 2017). Accordingly, it is an interesting question whether perceptual decoupling similarly occurs for selective internal attention as operationalized in the SAT, where internal attention needs to be directed to previously memorized items. In principle, such a perceptual decoupling could explain the internal shielding benefit, which we aimed to test in the current study.

To this aim, we collected EEG measurements while participants performed the SAT. We focused our analysis on visual ERPs generated in response to the cue, which informed participants about the modality to be selected (either external or internal) when processing the upcoming target, and the external and internal target themselves. For each of them, we performed a standard amplitude measurement at selected electrode positions and assessed whether the ERP component changed depending on two factors concurrently: attention type (external; internal) and switch type (repeat; switch). For the cue, we analyzed the contingent negative variation (CNV) component, which reflects a preparatory signal for the upcoming stimulus, which might differ for external and internal trials (Brunia, 1988). We also aimed to analyze the cue-locked P1 and P2 components (e.g., Verschooren, Schindler, et al., 2021), but a biphasic peak for the P1 rendered the interpretation difficult (see the Appendix for analysis and a discussion in the Future Directions and Limitations section). For the target, we focused our analysis on the P1, N1, and P2 components. If perceptual decoupling underlies the internal shielding benefit, we would expect it to be stronger for internal-repetition trials, where internal attention can be efficiently maintained according to the associative interference interpretation. However, on internal-switch trials, perceptual decoupling should be disrupted, due to a working-memory update that nullifies attentional shielding. We would expect reductions in early

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visual components, reflecting reduced sensory processing (see Kam & Handy, 2013, for a review).

METHODS

Participants

We recruited 37 participants for the experiment through Sona, an online recruitment platform hosted by Ghent University. We based our sample size on our previous EEG study investigating switches between external and internal attention (Verschooren, Schindler, et al., 2021). Ethical approval for this study was obtained from the Faculty of Psychology and Educational Science at Ghent University, and all participants signed an informed consent. The participants were paid €30 for their participation. After rejecting one participant for a technical error during data collection, 36 remained in the final sample. A post hoc sensitivity analysis indicated we could capture a minimal effect size of $\eta_p^2 = .19$ for a 2 × 2 interaction with 80% power, given this sample size and design.

Materials

We used 16 stimuli from a stimulus set of nonverbalizable black line drawings (Endo, Saiki, Nakao, & Saito, 2003). Participants were randomly assigned eight of these stimuli at the start of the experiment. For each participant, four figures were used as the external set and four different ones for the internal set. We counterbalanced the specific stimuli that were used for the external versus internal set for each participant. The internal figures were scrambled offline to use in the internal trials, to equate the amount of visual stimulation without revealing the stimulus identity. The stimuli were presented on a white background (800 × 600 pixels) in squares (100 × 100 pixels) equidistant from the center of the screen in a 2 × 2 array, with the probe (100 × 100 pixels) appearing centrally.

Procedure

Participants were seated in front of a computer in a dimly lit room, with their heads restrained by a with chin rest, placed approximately 60 cm away from a 19-in. CRT monitor (1600 × 1200 resolution at 75 Hz). The experiment was programmed in the PsychoPy2 library (Peirce et al., 2019) in Python (Version 3.8). The instructions were presented in Dutch on screen. Participants were instructed to maintain central fixation throughout the task. The experiment began with an external and internal training phase (order counterbalanced over participants). The external training phase was included to equate the amount of familiarity and training that participants have with the external and internal stimuli before the onset of the actual experimental task (see Verschooren, Liefooghe, et al., 2019, Experiment 2). On each trial of the external training phase, the four external stimuli appeared in a 2 × 2 array, with one of the locations selected as the target for this trial by a blue frame. The locations of these stimuli were selected randomly on each trial (i.e., which stimulus appeared in which of the four possible locations), as was the selected target location. After 250 msec, a central probe was presented, which was either the same as the selected target stimulus, or a different one from the same set of stimuli. Participants had to decide whether the probe and target stimulus matched or mismatched. During the training phase, the stimuli remained on screen for 10 sec or until response. After each trial, feedback was provided in Dutch ("Correct!," "Error!," "Too late") for 1 sec, after which the next trial started. The next phase of the experiment only started once the accuracy criterion was reached, defined by the conjunction of at least 18 correct trials and a total accuracy of 85%. For the internal training phase, the four stimuli were presented first with the instruction to memorize them and their locations. They remained on screen until the space bar was pressed (self-paced memorization). Then, for each trial of the internal training phase, the figures appeared in scrambled format in one of the four locations in the array (i.e., participants had to retrieve the stimuli form memory), with one of the four locations selected by a blue frame. After 250 msec, a central probe appeared and participants had to indicate whether this stimulus matched or mismatched with the stimulus previously memorized in the targeted location. The stimuli remained on screen for 10 sec or until a response was given. Feedback was provided in Dutch for a correct response ("Correct!") and responses outside the response window ("Too late"), as in the external training phase. However, different to the external training phase, when participants made a mistake, the four stimuli appeared again to allow the participants the opportunity to memorize them again, with the message "Error!" above it and the instruction to press the space bar when they were ready to continue the experiment. The same accuracy criterion as for the external training phase had to be reached to end the internal training phase. This criterion was set to assure that all participants had a strong (and equal) memory representation of the stimuli and their location.

In the experimental task, each trial with a fixation cross for a jittered duration in between 300 and 500 msec, after which a cue was presented for 1 sec, indicating whether the current trial was an external ("E") or internal ("I") one. After the cue, the stimuli would appear (i.e., the stimuli themselves in external trials or their scrambled version in internal ones) in a 2 × 2 array. Simultaneously, the target location would be selected with a blue frame and the central probe appeared. The stimuli remained on screen for 2 sec or until a response was provided.

The main experiment consisted of one practice block and eight experimental blocks, consisting of 82 trials each. The external and internal training phases described above appeared only before the practice block and the first experimental block. The trial sequence of the experimental blocks was pseudorandomized to ensure that each

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participant had an equal number of external and internal trials (i.e., whether the stimuli appeared on screen or had to be retrieved from memory), repetition and switch trials (whether the current trial type—external or internal—was the same as the previous), and match and mismatch (whether the probe matched the target) trials, and their combinations (e.g., not more mismatch trials for the internal than the external condition). The stimulus locations (for external trials specifically), target location, and probe identity were randomized on each trial, however. The response keys were the "D" and "K" keys for match- and mismatch responses in both the training phases and the experimental trials (counterbalanced over participants). The experimental variables of interest were Attention Type (external; internal) and Switch Type (repeat; switch), which resulted in a 2 × 2 design. After removing the practice block trials and the two warm-up trials at the start of each block, this resulted to 160 trials per cell of the design.

EEG Recording and Preprocessing

The EEG signal was recorded from 64 BioSemi active electrodes (www.biosemi.com). The sampling rate was set to 512 Hz. The electrodes were fitted into an elastic cap following the BioSemi position system (i.e., electrode positions are radially equidistant from Cz; www.biosemi.com/headcap.htm). As part of this setup, two distinct ground electrodes were used: a Common Mode Sense active electrode and a Driven Right Leg passive electrode. These electrodes formed a feedback loop, allowing for the measurement of the average potential in close proximity to the reference point in the A/D-box (www.biosemi.com/faq/cms&drl.htm). In addition, four extra electrodes (EOG) were utilized to monitor horizontal and vertical eye movements. These EOG electrodes were positioned at the outer canthi of the eyes, as well as above and below the left eye.

EEG preprocessing was carried out in the MNE library (Gramfort et al., 2013) in Python (Version 3.9.7). We used a band-pass filter between 0.1 Hz and 30 Hz and down-sampled the signal from 512 to 250 Hz. For each trial, epochs were selected for the cue and target separately. For the cue, these epochs were selected from 200 msec before onset until 1000 msec after onset. For the target, these epochs were selected from 200 msec before onset until 600 msec after onset. For each condition, 160 trials were available before preprocessing, but only the trials where the current and previous one was responded to correctly were maintained for the analysis. To fit the independent components analysis (ICA), we used a more highly filtered version of the data (between 1 and 30 Hz), as recommended by MNE. ICA components for blinks were automatically selected and removed by calculating the correlation with the frontal Fp1 and Fp2 channels, where the blinks were expressed more clearly than in the EOG electrodes (see the Appendix for an additional analysis of the blinks per condition). This automatic selection was manually inspected and corrected where necessary. Following the ICA, we implemented the autorejection algorithm (Jas, Engemann, Bekhti, Raimondo, & Gramfort, 2017) and applied a fixed peak-to-peak threshold (150 mV) to remove further artifacts. We visually inspected the raw epochs and power spectra to ensure that the preprocessing procedure worked well. Finally, bad channels were interpolated (0 channels: $n = 25$, 1 channel: $n = 5$; 2 channels: $n = 5$, 3 channels: $n = 1$) and rereferenced the data to the average of all electrodes. Overall, 10.17% (SD = 25.42%) of all epochs were removed. There were no significant main effects or interaction effect at the level of the cue, Fs(1, 35) < 2.91, ps > .10, η_p^2s < .08, or target, Fs(1, 35) < 1.00, ps > .33, η_p^2s < .03, in the numbers of removed epochs per condition.

Data Analysis

Behavior

We preprocessed the behavioral data in RStudio (RStudio team, 2022; Version 2022.7.2.576) with the libraries *tidyverse2* (Wickham & RStudio, 2023), lme4 (Bates et al., 2024), and *emmeans* (Lenth et al., 2024). We removed all training trials, the trials of the practice block, the first two trials of each experimental block, and trials with a RT that was faster than 150 msec. For the RT analysis, we further removed all error trials and trials preceded by an error trial. In addition, we planned to remove participants scoring lower than 60% accuracy, but none fit that criterion. We analyzed the data using a generalized linear mixed model approach, that is, an inverse Gaussian distribution for the RT data and a binomial distribution for the ER data, with log link functions (see Verschooren, Liefooghe, et al., 2019).

We next analyzed the data to determine that there is a cost associated with switching compared with repeating and that this cost differs between external and internal trial types. For both analyses, we fit the most complex model with Attention Type and Switch Type as fixed effects (including their interaction) and subject as random effect. For these models, we provided estimates for their coefficients, along with their 95% confidence intervals and associated p values. These values were calculated using the asymptotic Wald test, which does not provide degrees of freedom. We transformed the estimates for the planned contrasts (external-switch vs. external-repeat and internal-switch vs. internal-repeat for the interaction effect) back to the response scale. The 95% confidence intervals and p values for these contrasts were also obtained using the asymptotic Wald tests and were adjusted for multiple comparisons using the Tukey method. We visually inspected the assumptions by examining residual plots. These plots did not reveal any obvious deviations from homoscedasticity or normality for the residuals of the generalized linear mixed model.

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ERP Analysis

We selected electrodes and time windows based on a collapsed localizer approach (Luck & Gaspelin, 2017; see Figure 2). With this approach, an average waveform is created across the conditions that will be compared in the actual analyses. The timing and scalp distribution from this collapsed waveform are used to select the analysis parameters for the noncollapsed data. Although these parameters are selected based on the actual data with this approach, biases are avoided by considering the global field power of the collapsed waveform, rather than visual differences between conditions of interest. The electrodes were selected based on the topography at the peak of this waveform. For the cue-locked CNV component, we selected electrodes Cz, FCz, C2, FC2, FC4, and FC6 (Figure 2A; see the Appendix for the cue-locked P1 and P2 components). For this component, we averaged the mean amplitude for the selected electrodes around a window of approximately 100 msec (i.e., 31 frames around the peak [973 msec], which crossed the end of the epoch). For the target-locked components (Figure 2B), we selected electrodes PO8, P8, PO7, and P7 for the P1 component, electrode O1, O2, Oz, and POz for the N1 component, and electrodes O1, O2, Oz, POz, and Iz for the P2 component. For the P1 and N1 components (both cue and target), we averaged the mean amplitude for the selected electrodes over a time window of 23.4 msec (i.e., six samples) around the peak amplitudes (145 and 211 msec, respectively). For the P2 component, we averaged the mean amplitude for the selected electrodes over a time window of 82 msec (i.e., 21 samples) around the peak amplitude (418 msec). We used these mean values for each subject in a repeated-measures ANOVA for each component of interest, testing for the main effects and interactions between Attention Type and Switch Type.

RESULTS

Behavior

The analysis of the RT data revealed main effects for Attention Type ($B = -0.03, t = -21.0, p < .001$) and Switch Type ($B = -0.2, t = -12.2, p < .001$). Participants were slower on internal compared with external trials and on switch compared with repetition trials (see Figure 3A). In addition, the interaction between these two factors was significant ($B = 0.01, t = 3.7, p < .001$). Transformed back to the original response scale, the model estimate for the external switch cost was 17 msec (95% CI [10, 24]) and, for the internal switch cost, it was 34 msec (95% CI [26, 41]; see Figure 3B). The model for the ER data showed a significant effect for attention type only ($B = 0.13, t = 5.4, p < .001$). Transformed back to the response scale, the model estimated the accuracy at 93% (95% CI [91.3, 94.2]) for external trials and 91% (95% CI [89.1, 92.7]) for the internal ones.

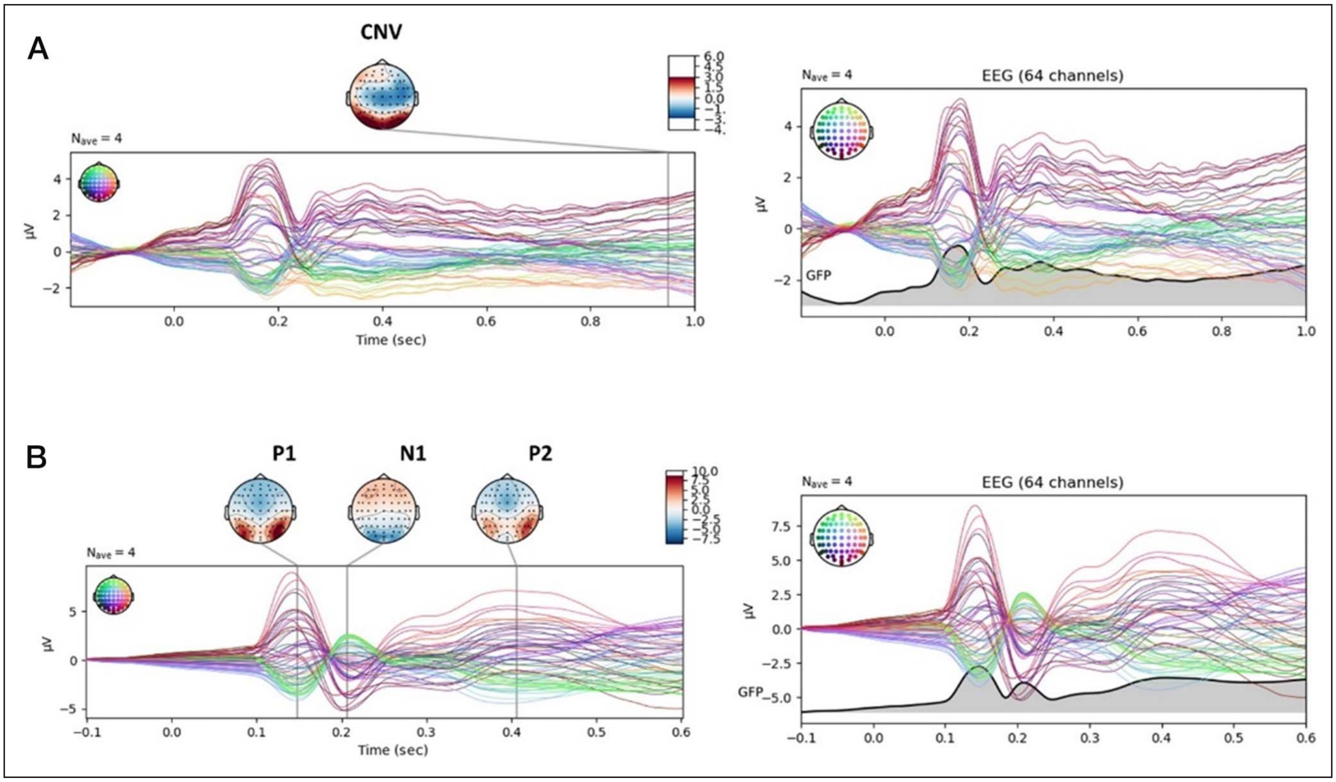

Figure 2. Collapsed localizer and global field potential. (A) Collapsed localizer (left panel) and the global field potential (right column) averaged across the four conditions and time-locked to the cue. The selected components are the P1, P2, and CNV, for which topographical maps are provided. (B) Same as above, but time-locked to the target instead. The P1, N1, and P2 are the selected components.

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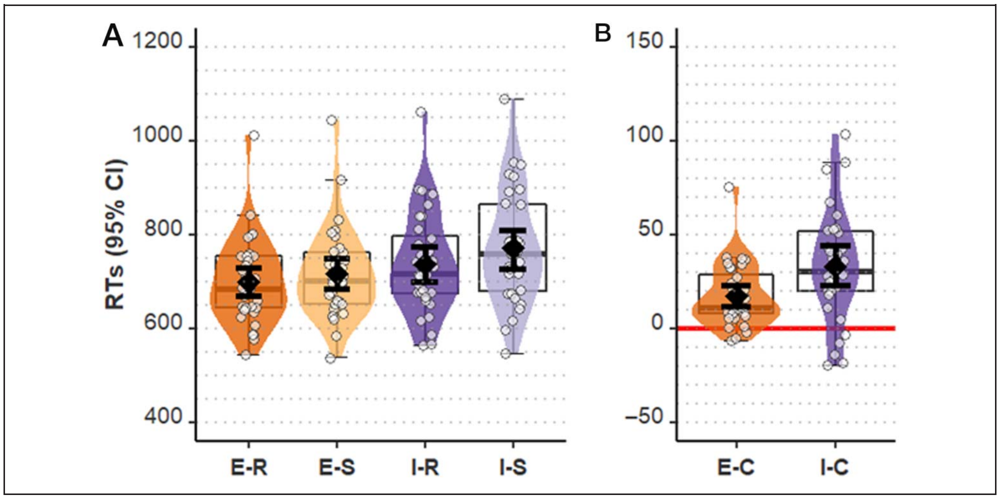

Figure 3. RTs. (A) RTs (95% CI) for each condition separately. (B) Switch cost for each attention type (E-C = external cost; I-C = internal cost).

ERP Analysis

Cue

CNV. The main effect of Attention Type was significant, $F(1, 35) = 17.16, p < .001, \eta_p^2 = .33$, with higher CNV amplitudes for internal compared with external trials. There was no significant effect for Switch Type, $F(1, 35) = 0.56, p = .46, \eta_p^2 = .02$, nor for the interaction between Attention Type and Switch Type, $F(1, 35) = 3.49, p = .07, \eta_p^2 = .09$ (see Figure 4C).

Target

P1. The main effect of Attention Type was significant, $F(1, 35) = 4.76, p = .036, \eta_p^2 = .12$, with higher P1 amplitudes for external compared with internal trials. We did not find a significant effect for Switch Type, $F(1, 35) = 1.11, p = .30, \eta_p^2 = .03$, or for the interaction between Attention Type and Switch Type, $F(1, 35) = 1.40, p = .25, \eta_p^2 = .04$ (see Figure 5A).

N1. For the target N1, there was a significant main effect of Attention Type, $F(1, 35) = 11.55, p = .002, \eta_p^2 = .25$, with larger N1 amplitudes for external compared with internal trials. The effects for Switch Type, $F(1, 35) = 0.40, p = .53, \eta_p^2 = .01$, or its interaction with Attention Type were not significant, $F(1, 35) = 0.35, p = .56, \eta_p^2 = .01$ (see Figure 5B).

P2. For the target-locked P2, we found a main effect of Attention Type, $F(1, 35) = 10.51, p = .003, \eta_p^2 = .23$, with a larger amplitude for external trials than internal trials. There was no main effect of Switch Type, $F(1, 35) = 1.62, p = .21, \eta_p^2 = .04$. We did find a significant interaction between Attention Type and Switch Type, $F(1, 35) = 8.00, p = .008, \eta_p^2 = .19$ (see Figure 5C). Post hoc tests showed that while the amplitude on internal switch was significantly smaller than on internal repeat trials ($d = 0.38, t = 2.88, p_{\text{holm}} = 0.02$, Cohen's $d = 0.11$), no significant difference was present for external switch and repetition trials ($d = 0.14, t = 1.04, p_{\text{holm}} = 0.30$, Cohen's $d = 0.04$).

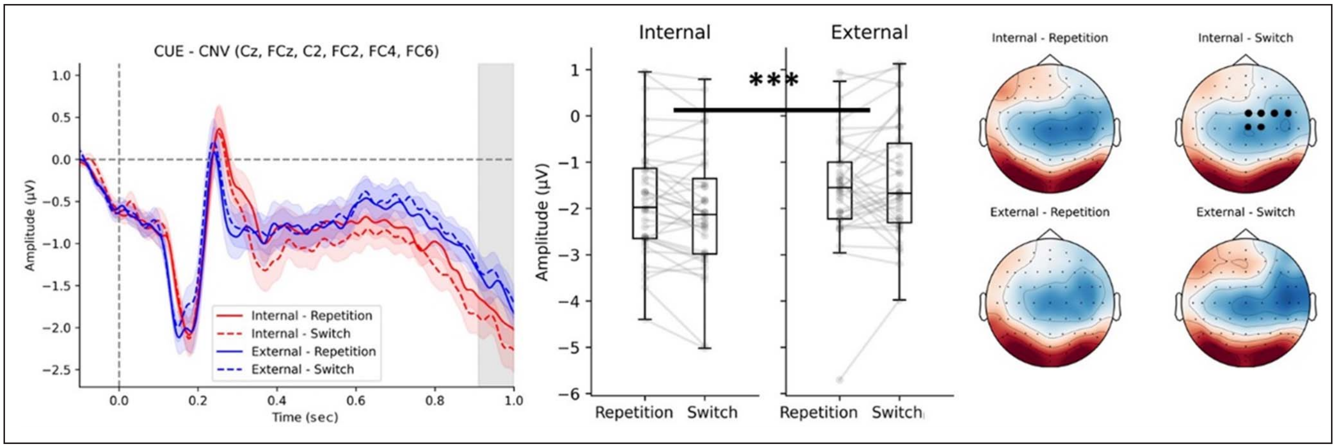

Figure 4. EEG results time-locked to the cue. CNV component plotted over time (in µV, error bars representing within-subject 95% CI; left column), box plots for the mean of the selected time window around the peak (middle column), and voltage maps for the four conditions of interest (right column). Significance: $^*p < .05$; $^{**}p < .01$; $^{***}p < .001$.

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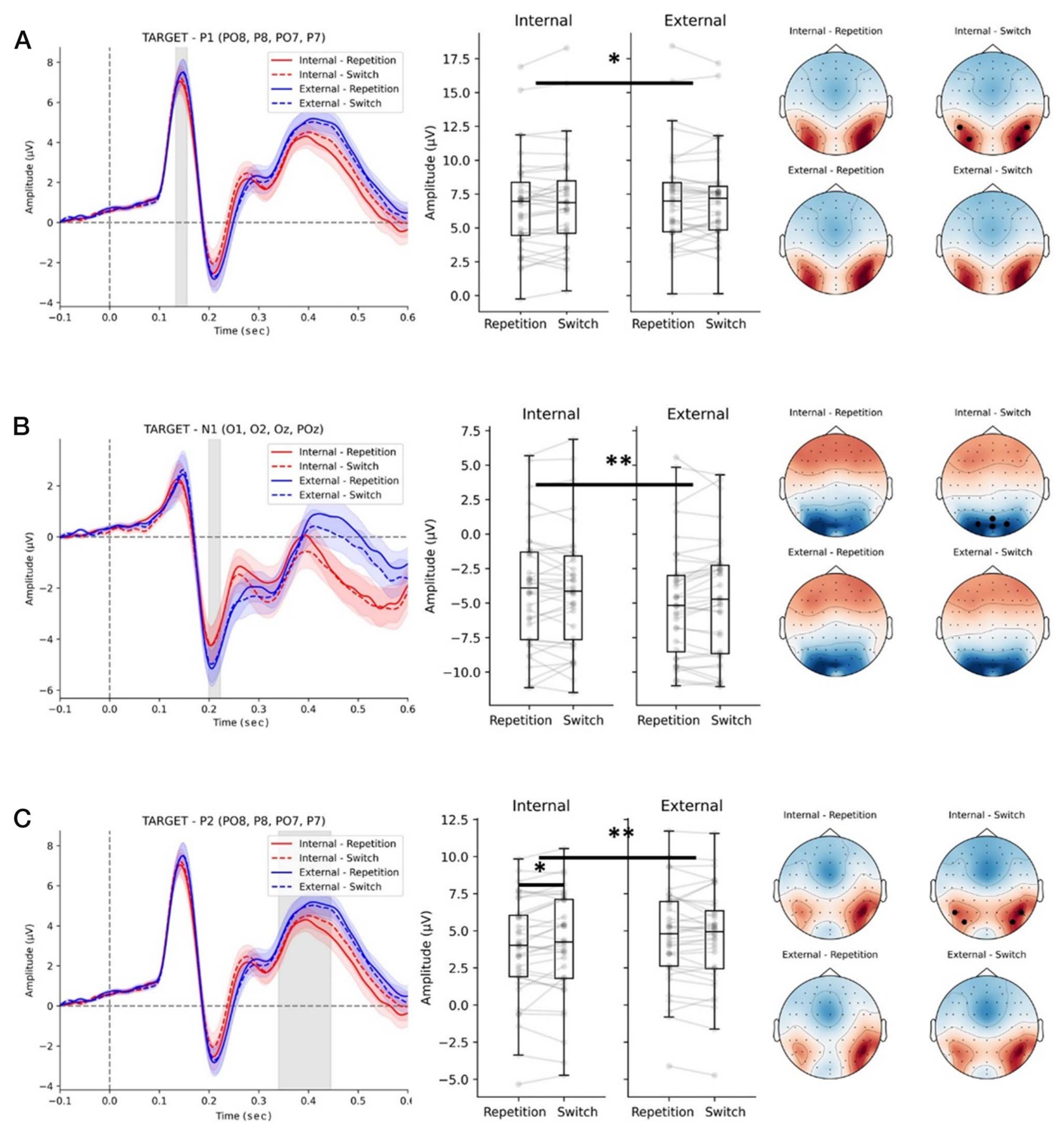

Figure 5. EEG results time-locked to the target. Target-locked averaged ERP waves plotted over time (in μV, error bars representing within-subject 95% CI; left column), box plots for the mean of the selected time window around the peak (middle column), and voltage maps for the four conditions of interest (right column) for the P1 (A), N1 (B), and P2 (C) components. Significance: *$p < .05$; **$p < .01$; ***$p < .001$.

DISCUSSION

In this study, we investigated whether the cost asymmetry for switches between external and internal attention could be accounted for by perceptual decoupling, in line with an internal shielding benefit. We recorded 64-channel EEG while participants used either external or internal attention, and either switched between these two modalities or repeated them, to determine the neural signature of the cost asymmetry. At the behavioral level, we replicated the switch asymmetry in terms of RT costs, with participants showing a larger cost for switching toward internal than toward external attention (Wang et al., 2024; Hautekiet et al., 2023; Verschooren et al., 2020; Verschooren, Liefooghe, et al., 2019).

Our EEG results revealed three different stages of processing during these switches. First, time-locked to the

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cue, the ERP analysis showed a larger CNV component for internal trials than external ones, suggesting that participants prepared for the internal trials by directing attention internally before target onset. As there was no difference in CNV amplitude for switches toward internal trials compared with repeating internal trials, this process appears to be unspecific and not dependent on switching versus repeating the attentional state. Second, time-locked to the target, we found reduced amplitudes for the P1 and N1 components on internal trials compared with external ones, which indicate early spatial attention effects following target onset and are compatible with perceptual decoupling. These reductions are potentially a continuation of the internally directed attention already triggered before the trial onset, as reflected in the cue-related CNV. Finally, we found that that during target processing, the P2 amplitude was larger for switch compared with repeat trials during internal attention, but not during external attention. Such increases may represent a failure of perceptual decoupling on internal switch trials, which can explain the cost asymmetry and provides some insight into the mechanism underlying it. In the next sections, we discuss these novel results in more detail and examine their implications for theories of attention.

Differences in Preparation for External and Internal Trials

To begin with, the ERP analysis time-locked to the cue revealed an increased amplitude of the CNV component for internal compared with external trials. The CNV component tracks a variation of cognitive, attentional, and motivational factors, most notably motor preparation and stimulus anticipation (van Boxtel & Brunia, 1994; Brunia, 1988). In the current context, this CNV amplitude difference reflects a difference in preparation between external and internal trials. Increased CNV amplitudes on internal trials indicate that participants exhibited a larger anticipatory reconfiguration of attention, which either implies that they were placing the cognitive system in a retrieval mode that withdraws attention away from external input and allows for efficient processing of internal information (e.g., Tulving, 1983; see also Long, 2023; Tarder-Stoll et al., 2020) or were actually retrieving the stimulus set from memory before trial onset (e.g., Brunia, 1988). We did not find that this effect interacted with trial transitions, that is, whether the current trial repeated or switched between attention state of the previous trial, which implies that this process is nonspecific. One interpretation of this nonspecificity is that participants did not maintain the retrieved stimuli from trial to trial, in which case one would expect that CNV amplitude would be reduced when an internal trial is repeated. That is, if participants would maintain the internal information after the trial, there would be a benefit when the internal trial is repeated, which would be reflected in a CNV reduction for internal repetition trials specifically. That being said, it should be noted that there was a trend for an interaction with increased CNV amplitudes for internal switch compared with internal repetition trials. Even though it would likely be only a small effect, an interesting avenue for future research is to target the CNV specifically to determine whether such an interaction might occur under different conditions.

In summary, at the cue level, the theoretically most interesting effect is the increased amplitude for the CNV component on internal trials. This CNV effect reflects differences in preparation for internal compared with external trials, potentially in terms of withdrawal of attention from external input. We will integrate this finding with the effects observed at the target level further on.

Blunted Sensory Response on Internal Trials Immediately Following Target Onset

When considering the ERPs time-locked to the target, our analysis revealed reduced amplitudes on internal trials for the P1 and N1 components. The P1 component, which is an early component that is most outspoken over lateral occipito-temporal scalp regions, reflects the early stages of visual processing and is involved in the initial encoding and analysis of visual information. This component is strongly affected by visuospatial attention, with increased amplitudes and enhanced processing for attended stimuli, and reduced amplitudes when attention is directed elsewhere (e.g., (Hillyard, Vogel, & Luck, 1998; Luck & Hillyard, 1994). The reduction in P1 amplitude observed on internal trials thus indicates that attention was directed away from the external input, most likely toward the task-relevant internal information. Moreover, this withdrawal of attention from external input is consistent with the cue-locked CNV effect, which showed differential preparation for internal compared with external trials. This difference in preparation could signify an inward focus on the memorized stimulus, that is, attention being already drawn inward. For the N1 component, we found a similar reduced amplitude for internal trials. The N1 component can be interpreted in a similar vein, with more negative amplitudes for attended stimuli than nonattended stimuli, especially when visual discrimination is required, as used here with the SAT (Handy, Soltani, & Mangun, 2001; Hillyard et al., 1998; Luck & Hillyard, 1994).

As examined in the introduction, a blunted N1 and P1 amplitude in response to stimuli has been found to characterize perceptual decoupling during mind wandering (see Kam et al., 2022, for a review). When considered in the light of our current findings, this perceptual decoupling process seems to be a common characteristic of both self-generated, spontaneous internal thought and more goal-directed, selective internal attention. Interestingly, our ERP findings thus indicate that perceptual decoupling is not a feature of off-task behavior specifically, but of internally directed cognition in general, which is what mind wandering and selective internal attention share in

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common (see Verschooren & Egner, 2023), a point on which we elaborate below.

Taken together, the reduced amplitudes for the P1 and N1 components suggest that at the onset of the target when internal attention needed to be used, participants had already decoupled attention from the current sensory input and were directing it to internal, memorized information, whereas on external trials, attention likely remained coupled to external, sensory input. This process might already be instigated before trial onset, as can be seen in the CNV effect time-locked to the cue. However, as there was no interaction effect for the P1 or N1 component, these effects cannot explain the observed switch cost asymmetry at the behavioral level. To explain it, we need to turn to a later processing stage following target onset, which we do in the next section focusing on the P2 component.

Disrupted Perceptual Decoupling Following External Trials

Our ERP analysis of the P2 component provided evidence for an interaction effect, which had a similar signature as the asymmetrical costs found at the behavioral level: The P2 showed a reduction on internal repetition compared with switch trials, an effect that was absent for external trials. When we interpret this difference on internal trials in the light of a perceptual decoupling process, it implies that perceptual decoupling was less effective on internal switch than internal repetition trials, as the P2 amplitude on switch trials was less reduced. This interpretation makes intuitive sense, as participants' decoupling process has likely been disrupted by the intervening external trial. Moreover, seen in this light, the cost asymmetry at the behavioral level can potentially be explained: Participants are additionally slower on internal switch trials, as their attention is not yet decoupled sufficiently from perceptual information, which interferes with stimulus processing. That being said, it should be noted that the P2 component is not often used as an EEG marker of perceptual decoupling. As a matter of fact, studies that have examined the P2 component during mind wandering in the past have reported mixed results. Whereas some researchers have found a reduced P2 component during mind wandering (e.g., Conrad & Newman, 2021; Xu, Friedman, & Metcalfe, 2018), suggestive of perceptual decoupling, others have actually found an increase in the P2 component during mind wandering (e.g., Compton et al., 2024; Braboszcz & Delorme, 2011). Moreover, a recent systematic review included the P1, N1, and P3 component as markers of perceptual decoupling during mind wandering, but not the P2 component (Kam et al., 2022).

As an alternative interpretation, these increases in P2 amplitude on internal switch trials might actually reflect an enhanced recruitment of internal attention. That is, although the P2 component is primarily associated with early perceptual and attentional processing (Luck & Hillyard, 1994), it has also been linked to the engagement of internal attention. For example, P2 amplitude is increased when directing attention internally to information in working memory (e.g., Jokisch & Jensen, 2007; Sauseng et al., 2005). Such selective internal attention is taxed during the SAT, as participants are instructed to select one internal representation among other distracting information in memory. As such, this interaction effect could indicate that more selective internal attention is required on switch compared with repetition trials, because the internal template is less sharp after a preceding external trial. Such an interpretation would imply the presence of additional internal attentional recruitment on internal switch trials. However, this interpretation appears to have limited explanatory power, as it assumes two opposite effects in the P2. On the one hand, it assumes that the P2 is reduced on internal compared with external trials due to perceptual decoupling, which enhances attention to internal information. On the other hand, it would assume that the P2 is increased on internal switch compared with repetition trials, which would also signify enhanced internal attention. Although this is in principle possible, it is not parsimonious and does not explain cost asymmetry specifically. As such, interpreting both the difference between external and internal trials in general, and the difference between internal switch and internal repetition trials specifically, in terms of perceptual decoupling is most sensible and provides a more straightforward explanation for the switch cost asymmetry. That is, participants are slower on internal switch compared with repetition trials due to ineffective perceptual decoupling.

In summary, the interaction effect for the P2 component, with an increased amplitude on internal switch compared with internal repetition trials, encourages us to speculate that a disrupted perceptual decoupling process underlies the switch cost asymmetry. That is, when participants repeated an internal trial, they were able to stay in a stable internal attentional set, promoting further perceptual decoupling. On switch trials, however, attention had previously been directed to the external environment, interfering with the attentional set, which needed to be reengaged. For external trials, no such process took place. Although the P2 component is not often interpreted in terms of perceptual decoupling in the mind-wandering literature, our current results suggest that it might actually reflect this decoupling process in the context of selective internal attention. Speculatively, these findings also suggest that there are two decoupling processes occurring sequentially: an early one reflecting the general engagement of internal attention (i.e., at the level of the P1 and N1), followed by a later one that more directly reflects internal shielding (i.e., at the level of the P2). These interpretations should be treated with caution, however, as we did not find evidence for direct correlations between the RTs and P2 amplitudes (see the Appendix and Future Directions and Limitations section). In the next section, we bridge this finding with existing behavioral accounts

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of the cost asymmetry and its broader theoretical implications. To anticipate this integration, we will argue that perceptual decoupling can provide a mechanism that underlies the internal shielding benefit of attention.

Integrating Perceptual Decoupling and the Internal Shielding Benefit

As examined in the Introduction, previous behavioral work has suggested that an internal shielding benefit underlies the switch cost asymmetry for external and internal attention (Verschooren & Egner, 2023; Verschooren et al., 2020). In a nutshell, this internal shielding benefit states that irrelevant information that has been encoded before in a similar context can interfere easily when attending externally. When attending internally, on the other hand, irrelevant external information can be shielded against more efficiently.

Our current ERP findings can be linked to and support this associative interference account. That is, the most likely interpretation of our current results, that is, in terms of failed perceptual decoupling, speaks directly toward an internal shielding benefit in itself. While the internal shielding benefit assumes that participants are able to protect their internal attentional state from intrusions by external information, the perceptual decoupling effect found here explains how this might occur: by decoupling the sensory cortices from higher order brain regions responsible for decision-making and behavior, which promotes a stable internal attentional set guiding behavior. Crucially, in doing so, the current ERP results and interpretation go beyond what is currently known in the existing cognitive neuroscience literature about the balance and regulation of external and internal attention. The decoupling process provides a mechanism through which internal information can be shielded when switching between both sources of attention. An interesting implication arising from this interpretation is that it might be less seamless to decouple external attention from internal sources of information than vice versa. Specifically, people can direct attention away from external sources of information, for example, through perceptual decoupling and/or diverting their gaze, but it might be more difficult to inhibit previously encoded information that automatically disrupts attentional processing.

More broadly, the associative interference account and the implied internal shielding benefit have been important for theorizing about the overall balance between external and internal attention, to which the current results also speak. This question is addressed by the Internal Dominance over External Attention hypothesis, which proposes that attention is actually biased toward internal sources of information (Verschooren & Egner, 2023). As such, this hypothesis can be seen as a generalized formulation of this internal shielding benefit. This generalized formulation relies on the observation that the balance of attention is largely determined by the volatility of the context (see Tarder-Stoll et al., 2020, for a review). In volatile contexts, attention needs to be directed more externally toward novel and potentially relevant information, whereas, in stable or familiar contexts, attention can be directed primarily internally, as one can rely more efficiently on previously encoded information. Similar arguments have been put forward in the context of predictive coding as well, where the reliance on top–down predictions versus bottom–up signals depends on contextual volatility (Yon & Frith, 2021). Within this framework, the brain is mostly concerned with its intrinsic processes and the maintenance of the correct internal milieu, with external events only minimally perturbing these dynamics (e.g., in the context of surprise). Crucially, this Internal Dominance over External Attention hypothesis acknowledges that some contexts are more conducive to external attention but presumes that there nonetheless exists a pervasive attentional bias toward internal information, as navigating stable and predictable environments has been the norm for our species. An internal shielding benefit, in this broader interpretation, simply means that when attending externally, internal information more easily draws attention than the other way around. Our new results further support this intriguing hypothesis by providing a potential mechanism for how attention can be drawn inward and protected from irrelevant or non-urgent external interference.

Future Directions and Limitations

Our study has shed novel light on the neural process underlying the internal shielding benefit of attention. Specifically, based on our results, we have proposed that the internal shielding is maintained through the decoupling of attention from early sensory input. This finding allows for a better understanding of asymmetrical switch costs, which are a robust signature of switches between external and internal attention at the behavioral level (Gresch, Boettcher, Gohil, et al., 2024; Gresch, Boettcher, van Ede, et al., 2024; Wang et al., 2024; Hautekiet et al., 2023; Calzolari et al., 2022; Verschooren et al., 2020; Verschooren, Liefooghe, et al., 2019; Dark, 1990) and speak to the overall balance between them (Verschooren & Egner, 2023). That being said, there are some limitations that should be addressed in future research.

First, when investigating differences between external and internal attention, it is important to equate the task demands and stimuli for the external and internal conditions as closely as possible, to ensure that the observed differences can be attributed specifically to external and internal attentional processes (Verschooren, Liefooghe, et al., 2019). Such equating of task demands and stimuli is even more important when aiming to interpret potential neural differences between external and internal attention. As such, it should be noted that even though the figures in the internal condition were scrambled to keep the early visual stimulation as close as possible to the external condition, differences remain between actual and

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scrambled figures that might affect the neural response, which do not directly reflect external versus internal attention. Although it is unlikely that such differences could account for the complex pattern of results observed here (i.e., an interaction effect at the P2 level), future studies might consider presenting the external stimuli on both the external and internal trials, with a cue being the main signal informing participants on the nature of the current trial. Although this approach might lead to other potential confounds (e.g., artificially increased external interference), the visual stimulation would be perfectly equated between conditions. It would be interesting to compare the results obtained from such an experiment to the ones obtained here.

Second, some caution is warranted for the interpretation of the perceptual decoupling effect observed here. To begin with, in the current study, we did not directly examine the link between the behavior and ERP components, as our design was not optimized for testing for correlations. Thus, as expected, there is no significant correlation effect ($r = .02, p = .82$; see the Appendix). We suggest that future studies should optimize their design for single-trial correlations between RTs and P2 amplitude. Moreover, in the context of perceptual decoupling, it might be valuable to consider experimental designs in future research that does not rely solely on visual information, but rather on auditory or other modalities (e.g., presenting a certain tone to signal the identity of the probe and target). In the current design, the visual information might increase perceptual decoupling to overcome interference. Alternatively, the presence of visual information might actually prevent or interrupt perceptual decoupling, as participants need even in internal trials to process the visual cues to ascertain the identity of the probe and the target. By replacing the visual cues with auditory ones, a more pure measure of perceptual decoupling might be obtained. In addition, future studies should also consider later signatures of perceptual decoupling, such as the P3 (e.g., Kam et al., 2022), as the (externally provided) target and probe information have been processed at this point. That being said, comparing external and internal conditions in a controlled manner will always be a matter of degree, as external information necessarily needs to be provided and accessed in the internal condition (e.g., the target identity for the current trial) and vice versa for the external condition (e.g., maintaining the task set).

Moreover, as mentioned above, the P1 and P2 components time-locked to the cue turned out to be difficult to interpret due to the presence of an unexpected biphasic peak for the P1. Given this limitation, we moved the analysis of these components to the Appendix and did not consider them for the interpretation of our results. This caveat in mind, taken at face value, we found a larger reduction in amplitude when switching toward external trials for the cue-locked P1, compared with repeating them, which did not occur for internal trials. This effect on external trials replicates our earlier finding where participants switched toward an external baseline task after completing an unrelated external or internal task before, which we interpreted as evidence for early resource sharing between external and internal attention (Verschooren, Schindler, et al., 2021). We also found an interaction effect for the P2 component, with an increase in amplitude for internal switch trials compared with internal repetition trials, which was absent for the external trials. Here again, however, the results might be affected by the biphasic peak of the earlier P1. A further complication relates to the latencies of these early components, which appears to be delayed on internal compared with external trials (see the Appendix, Figure A2), which might be confounded with the biphasic peak (i.e., the second peak for the P1 on external trials does coincide with the peak for the internal trials). Future research should investigate why such a biphasic peak appears solely following an external cue and whether it might affect the latencies of the external and trials.

A final caveat relates to the behavior of the eye. There is ample evidence that eye behavior is strongly associated with internal attention and perceptual decoupling (e.g., Korda et al., 2023; Benedek et al., 2017; Walcher et al., 2017). In the current study, we did not use an eye-tracker to collect eye behavior, but merely corrected for eye blinks based on the EEG signals. In the Appendix, we report an additional analysis comparing the presence of blinks for the different conditions of interest. Time-locked to the cue, we found more blinks in the external-switch condition compared with the other ones. Time-locked to the target, however, no significant differences emerged. As such, we are confident that differences in blinks cannot easily explain our main ERP finding, that is, the interaction effect at the level of the P2. Moreover, given that we did not reject blink artefact, but rather corrected for them, their influence on the ERPs should be minimal. That being said, the absence of outspoken differences for the external and internal trials in terms of eye-behavior is surprising, given their established relationship in the literature. This absence might be attributed to a lack of precise eye-behavior indices that can be obtained through eye-tracking and the instruction provided to the participants to maintain central fixation throughout the task, forcing more similar behavior for the external and internal trials. Future research should collect more detailed eye behavior, including blink duration, pupil dilation, saccades, and other indices, which might differ between external and internal attention and could provide more insights into the nature of perceptual decoupling when switching between external and internal attention (and internal coupling; Korda et al., 2023).

In summary, our findings open many novel avenues for future research into the role of perceptual decoupling in the internal shielding of attention. We hope that the research presented here can serve as a motivation and blueprint to delve deeper into this fundamental mechanism of attentional flexibility.

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Conclusions

We uncovered three different processing stages occurring during switches between external and internal attention. Following the cue, participants showed a larger CNV for internal than external trials, indicating differences in preparation for both trial types and a withdrawal from external input. During target processing, reduced P1 and N1 components on internal trials indicate perceptual decoupling. Most importantly, we observed an asymmetrical signature for the P2 component, which suggests that the internal shielding benefit is supported by efficient perceptual decoupling on internal repetition trials. As such, this perceptual decoupling mechanism might underly the behavioral cost asymmetry and can explain the internal shielding benefit, which has broad implications for the overall balance between external and internal attention.

APPENDIX

Cue-locked P1 and P2 Components

ERP Analysis

The cue-locked P1 and P2 components were selected based on the collapsed localizer approach presented in the main article (Luck & Gaspelin, 2017). Using this method, we selected electrodes O1, O2, PO7, and PO8 with a time window of 23.4 msec (i.e., six samples) and 82 msec (i.e., 21 samples) around the peak for the P1 (164 msec) and P2 (371 msec) component, respectively. The amplitudes in these time windows were averaged and subjected to a repeated-measures ANOVA with Attention Type and Switch Type as fixed effects. In addition, to analyze the biphasic peak present in the P1 component, we conducted two additional analyses centered around the early (148 msec) and late peak (176 msec; Figure A1B–C).

Results

P1. The repeated-measures ANOVA showed a main effect for Switch Type, $F(1, 35) = 5.30, p = .027, \eta_p^2 = .13$, with higher amplitudes for repetition compared with switch trials. There was no effect of Attention Type, $F(1, 35) = 0.85, p = .364, \eta_p^2 = .02$, but the interaction between Attention Type and Switch Type was significant, $F(1, 35) = 4.86, p = .034, \eta_p^2 = .12$ (see Figure A1A). More specifically, the P1 amplitude was smaller on external-switch than external-repetition trials ($t = 2.95$, $p_{\text{holm}} = 0.029$, Cohen's $d = 0.27$) whereas for internal trials, this difference was not observed ($t = 1.08$, $p_{\text{holm}} = 0.86$, Cohen's $d = 0.10$).

For the early peak of the P1, we found a significant effect of Attention Type only, $F(1, 35) = 12.91, p < .001, \eta_p^2 = .27$, with higher amplitudes for internal than external trials. For the late peak, we found a significant main effect for Attention Type, $F(1, 35) = 5.31, p = .03, \eta_p^2 = .13$, with higher amplitudes on internal than external trials, and for switch type, $F(1, 35) = 15.13, p < .001, \eta_p^2 = .30$, with lower amplitudes for switch compared with repetition trials. These main effects were further qualified by an interaction effect between them, $F(1, 35) = 6.36, p = .02, \eta_p^2 = .15$. Post hoc tests showed that although the P1 amplitude was lower for external-switch than external-repetition trials ($t = 3.48$, $p_{\text{holm}} = 0.007$, Cohen's $d = 0.30$), there was no such difference for internal-switch and internal-repetition trials ($t = 1.15$, $p_{\text{holm}} = 0.78$, Cohen's $d = 0.09$).

P2. For the cue-locked P2, the main effect of Switch Type was significant, $F(1, 35) = 5.15, p = .03, \eta_p^2 = .13$, but not of Attention Type, $F(1, 35) = 1.19, p = .18, \eta_p^2 = .05$. The interaction between both effects was significant, however, $F(1, 35) = 6.05, p = .02, \eta_p^2 = .15$ (see Figure A1D): Whereas the P2 amplitude was significantly smaller on internal-repetition trials than on internal-switch trials ($d = 0.69, t = 3.24$, $p_{\text{holm}} = 0.013$, Cohen's $d = 0.23$), this was not the case for external-switch compared with external-repetition trials ($d = 0.24, t = 1.11$, $p_{\text{holm}} = 0.81$, Cohen's $d = 0.08$).

Correlation P2 Component and Cost Asymmetry

Analysis

We conducted a Spearman correlation analysis between the RTs and P2 amplitudes using the stats library in RStudio (RStudio team, 2022; Version 2022.7.2.576). To do so, we merged the data sets with the averaged RT per condition per subject with the data set containing those values for the P2 amplitudes, averaged across the entire time window.

Results

The correlation between the RTs and P2 amplitudes was not significant ($r = .02, p = .82$; Figure A2).

Eyeblink Analysis

Analysis

To determine whether there were differences in eye blinks between the conditions, we ran an additional analysis in which we used the EOG channels to detect these events with the *find_eog_events* function in MNE (Gramfort et al., 2013). We report here the blink detection with a threshold of 100 mV (it should be noted that with a more liberal threshold of 50 mV, the results remained the same).

Results

Time-locked to the cue (see below), we find that the two main effects are significant. There are more blinks in the external compared with the internal condition, $F(1, 35) = 12.77, p = .001$, and more on switch trials compared with repetition trials, $F(1, 35) = 16.14, p < .001$. These main effects were qualified by a significant interaction effect, however, $F(1, 35) = 32.96, p < .001$. Post hoc tests revealed

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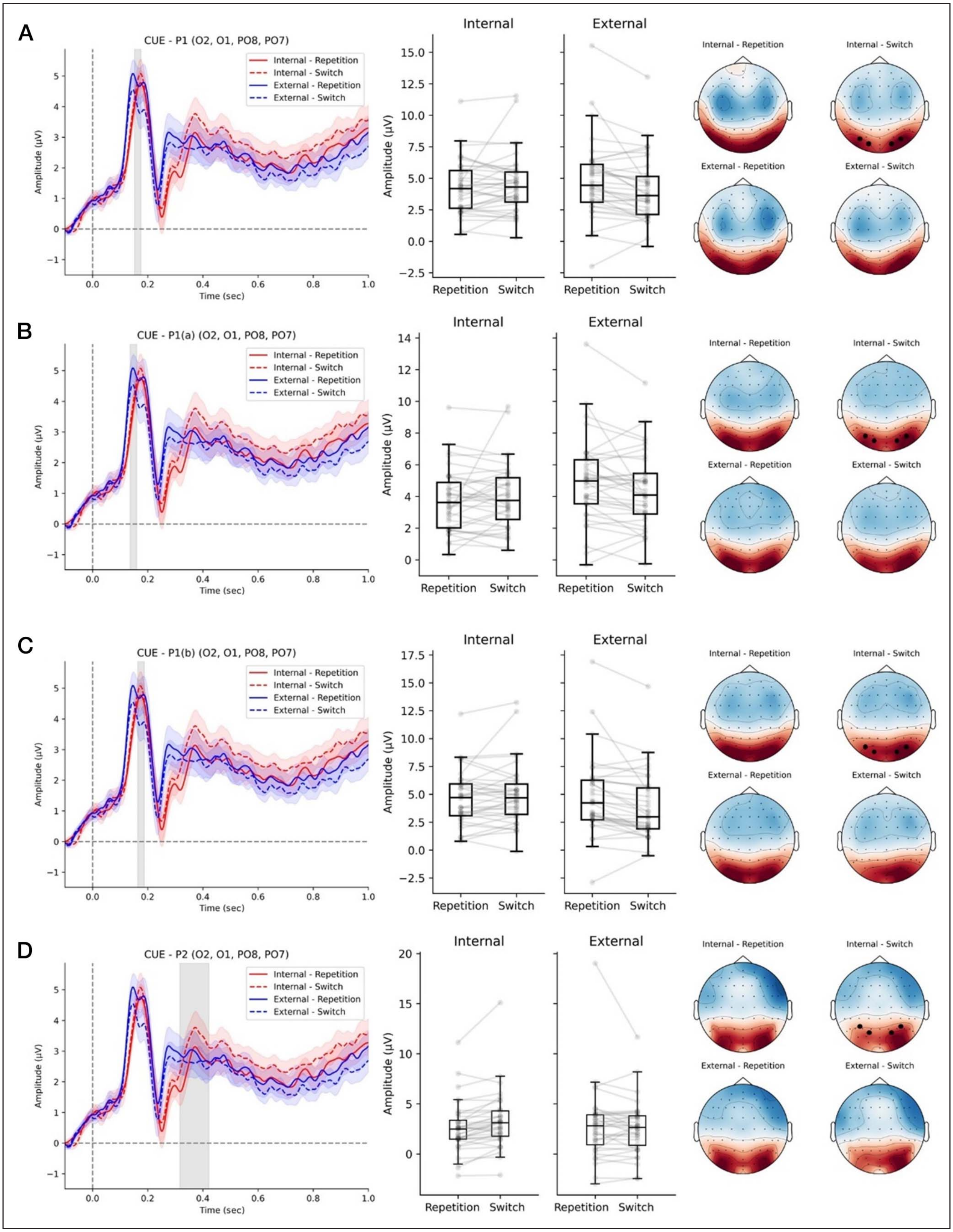

Figure A1. P1 and P2 components time-locked to the cue. Cue-locked averaged ERP waves plotted over time (in µV, error bars representing within-subject 95% CI; left column), box plots for the mean of the selected time window around the peak (middle panel), and voltage maps for the four conditions of interest (right column) for the P1 (A), early P1 (B), late P1 (C), and P2 (D) components.

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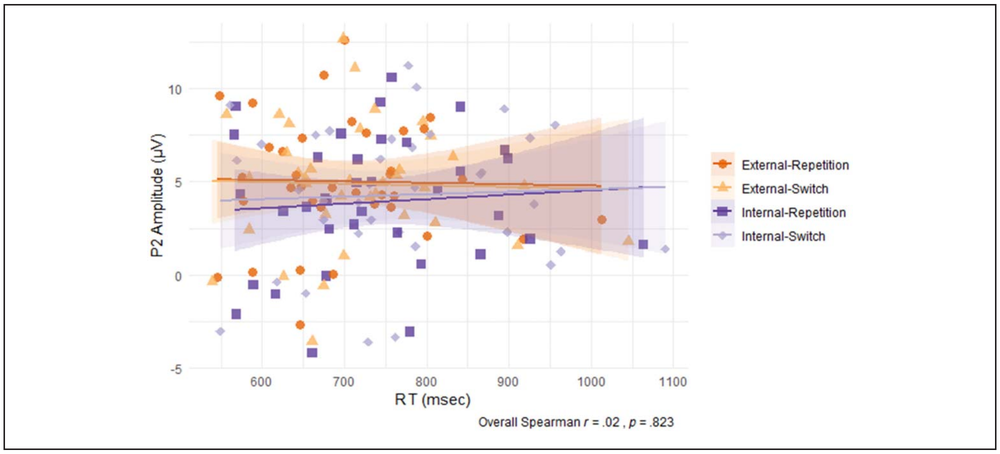
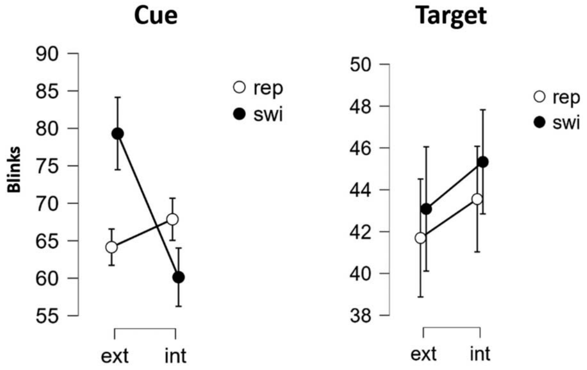
Figure A2. Correlation between RT and P2 amplitude.



that participants showed significantly more blinks on external-switch compared with external-repetition trials ($t = 6.21, p < .001$), but significantly less on internal-switch compared with internal-repetition trials ($t = 4.00, p < .001$).

Time-locked to the target, we did not find any significant differences in eyeblinks for the different conditions. That is, neither the interaction effect or the main effects are significant for this analysis, $Fs(1, 35) < 1.97, ps > .16$.



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Data Availability Statement

The experimental script, data, and analysis scripts can be found on a designated Open Science Framework repository (https://osf.io/y7pke/).

Author Contributions

Sam Verschooren: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Software; Visualization; Writing—Original draft. Luc Vermeylen: Data curation; Formal analysis; Visualization. Sam Boeve: Investigation. Gilles Pourtois: Conceptualization; Funding acquisition; Methodology; Resources; Supervision; Writing—Review & editing.

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Diversity in Citation Practices

Retrospective analysis of the citations in every article published in this journal from 2010 to 2021 reveals a persistent pattern of gender imbalance: Although the proportions of authorship teams (categorized by estimated gender identification of first author/last author) publishing in the *Journal of Cognitive Neuroscience* (*JoCN*) during this period were M(an)/M = .407, W(oman)/M = .32, M/W = .115, and W/W = .159, the comparable proportions for the articles that these authorship teams cited were M/M = .549, W/M = .257, M/W = .109, and W/W = .085 (Postle and Fulvio, *JoCN*, 34:1, pp. 1–3). Consequently, *JoCN* encourages all authors to consider gender balance explicitly when selecting which articles to cite and gives them the opportunity to report their article's gender citation balance. The authors of this paper report its proportions of citations by gender category to be: M/M = .677; W/M = .138; M/W = .077; W/W = .108.

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