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Perceptual decoupling underlies internal shielding benefit during switches between external and internal attention: Evidence from early sensory ERP components

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Abstract

People need to often switch attention between external and internal sources of information, i.e., external and internal attention, respectively. There has been a recent surge of research interest in this type of attentional flexibility, which revealed that it is characterized by an asymmetrical cost, being larger for switching toward internal than external attention. One potential explanation for this cost asymmetry is in terms of internal shielding, i.e., the maintenance of stable internal attention against external interference. However, it is currently unclear how this cost asymmetry is instantiated in the brain and how internal information might be shielded from external input during switches. 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 upcoming internal than external attentional selection, as reflected in the increased CNV 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 to repeating it, indicating more stable perceptual decoupling on internal repetition trials, in line with internal shielding. 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.

Keywords: *external attention; internal attention; attentional flexibility; perceptual decoupling; event-related potentials*

Introduction

Attentional selection is the prioritization of a subset of information from current external (sensory) or internal (mental) input (Chun et al., 2011). For example, external attention allows one to focus on reading this paragraph instead of attending to colleagues having a conversation in the background, while 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 et al., 2023; Verschooren & Egner, 2023). 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; see also Panichello & Buschman, 2021; Zhou et al., 2022). 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 (Honey et al., 2017; Servais et al., 2023; Tarder-Stoll et al., 2020; Verschooren, Schindler, et al., 2019). After some isolated efforts at the end of last century (e.g., Carlson et al., 1993; Dark, 1990; Weber et al., 1986), there has recently emerged a renewed interest in switches between external and internal attention (e.g., Burgess et al., 2007; Calzolari et al., 2022; Gilbert et al., 2005; Gresch, Boettcher, Gohil, et al., 2024; Gresch, Boettcher, van Ede, et al., 2024; Hautekiet et al., 2023; Poskanzer & Aly, 2023; Verschooren, Liefooghe, et al., 2019; Verschooren et al., 2020; Verschooren, Kessler, et al., 2021; Wang et al., 2024; Weilnhammer et al., 2023). 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; Hautekiet et al., 2023; Verschooren et al., 2020; Verschooren, Liefooghe, et al., 2019, Wang et al., 2024) has provided robust evidence that this cost is larger when switching attention from external to internal input than the other way around (see also Calzolari et al., 2022; Gresch, Boettcher, Van Ede, et al., 2024; Dark, 1990). It has been proposed that this cost asymmetry derives from an internal shielding benefit (Verschooren et al., 2020; Verschooren & Egner, 2023), but this proposal is based on mostly indirect evidence from behavioral findings, with direct evidence for internal shielding currently lacking. 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., Kam & Handy, 2013; Smallwood & Schooler, 2006, 2014). During perceptual decoupling, the primary sensory cortices are less responsive to external input, allowing for efficient processing of internal information. Given that mind wandering is a form of spontaneous internal attention, with several similarities to selective internal attention as defined here (Mittner et al.,

2016; Verschooren & Egner, 2023), 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 used 64-channel scalp electroencephalography (EEG) in this study, which allows to non-invasively track brain activity with a millisecond time resolution. As such, EEG can shed light on the bottleneck of attention switches and pinpoint its locus during information processing. Moreover, perceptual decoupling can be observed through the amplitude of early sensory ERP components, such as the P1 and N1 (Kam et al., 2022).

In a previous study based on a different paradigm than the SAT, we recorded 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, et al., 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 sharing of selection mechanisms between internal and external attention during such switches (Verschooren et al., 2021). Moreover, these ERP results suggested that early on following cue onset in the extrastriate visual cortex (i.e., likely when reconfiguration takes place in case of a switch of attention) 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 vs. 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 to this earlier task, as both directions of attention switches can be investigated with it (Hautekiet et al., 2024; Verschooren, Liefooghe, et al., 2019; Verschooren, et al., 2020; Wang et al., 2024). 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 **Fig. 1**). 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 (Hautekiet, Verschooren, et al., 2023; Verschooren, Kessler, & Egner, 2021; Verschooren, Liefooghe, et al., 2019; Verschooren, Pourtois, & Egner, 2020; Wang et al., 2024).

In follow-up research, it has been proposed that this cost asymmetry is due to an internal shielding benefit (Verschooren, Pourtois, & Egner, 2020; Verschooren & Egner, 2023). Specifically, Verschooren, Pourtois and Egner (2020) directly tested the predictions from three rival accounts, i.e., priming (e.g., Allport et al., 1994; Gilbert & Shallice, 2002; Yeung & Monsell, 2003a, 2003b), associative interference (e.g., Mayr et al., 2014; Waszak et al., 2003), and memory retrieval (e.g., Dark, 1990). The results fit best with the predictions from the associative interference account, which assumes that, over time, participants associate the stimuli with the task setting, which can lead to interference (e.g., Mayr et al., 2014; Waszak, et al, 2003; for reviews, see Monsell, 2003; Vandierendonck et al., 2010). Moreover, such an association can also be formed between the higher-order attentional settings required to carry out the task and the task context in the form of memory traces (see also Abrahamse et al., 2016; Braem & Egner, 2018; Chiu & Egner, 2017). Applied to switches between external and internal attention, this learning 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 irrelevant attentional settings. The larger switch cost for internal attention is explained by assuming that internal attention is stable on repetition trials (i.e., can be shielded efficiently from external attentional interference), resulting in a large difference between repetition and switch 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 trials, i.e., an internal shielding benefit (Verschooren, Pourtois, et al., 2020). In other words, while 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).

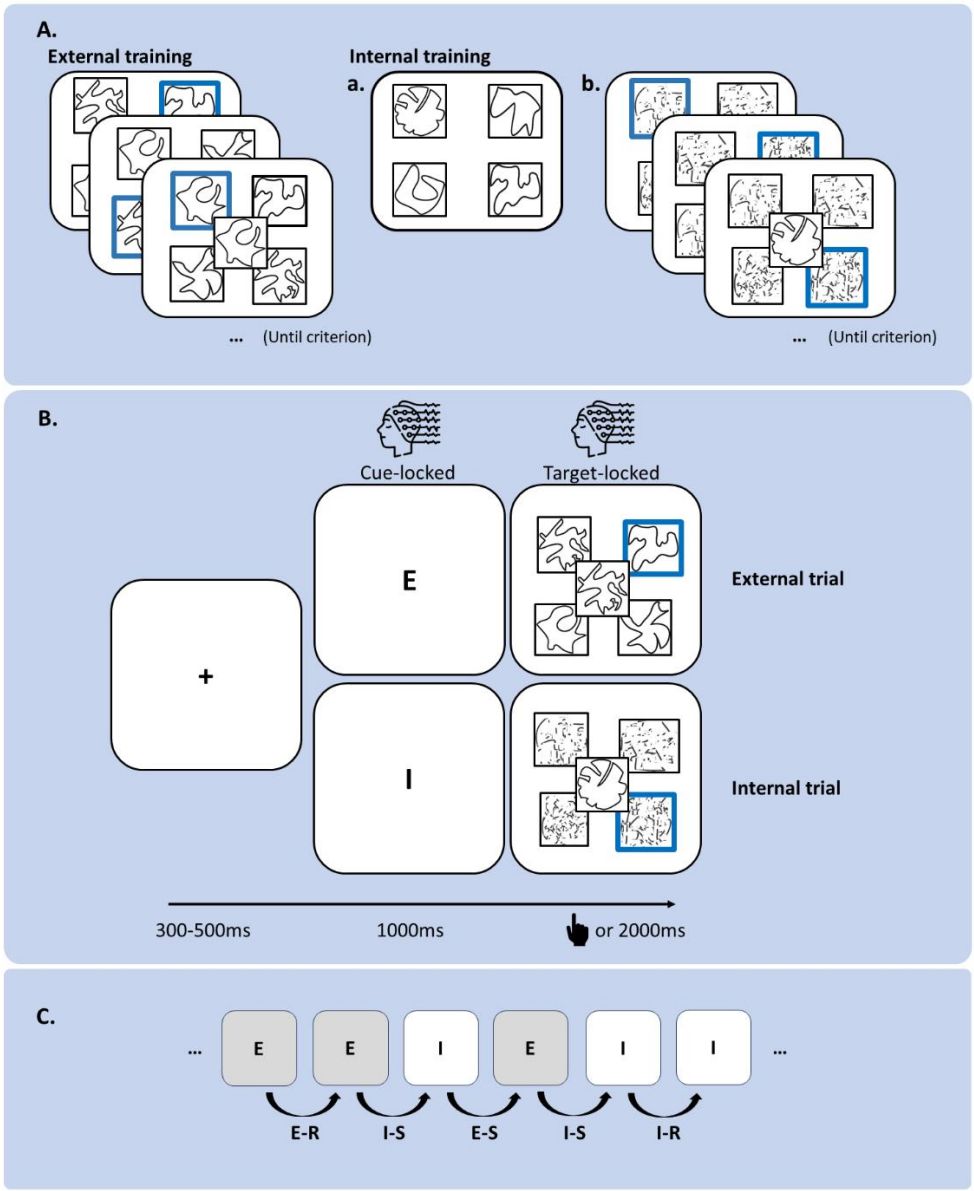
Further supporting this internal shielding notion, a recent study found that during hypervigilance, which results in an artificially increased focus on the external environment, the cost asymmetry disappeared (Wang et al., 2024). Behavioral modeling further revealed that this reduced cost asymmetry was 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 et al., 2011; Soto et al., 2008), sustained attention (e.g., Esterman & Rothlein, 2019; Thomson et al., 2015), mind wandering (e.g., Killingsworth & Gilbert, 2010; Mittner et al., 2016), 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 potential mechanism is perceptual decoupling, which has originally been 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 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 and Schooler, 2006; Schooler et al., 2011; Smallwood, 2013; see Kam & Handy, 2013, Kam et al., 2022 for a review). However, while the primary sensory cortices show a reduced activation, the secondary visual and somatosensory cortices remain nonetheless responsive (e.g., Wheeler et al., 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. While this finding is well-established in the mind-wandering literature, the evidence for other forms of internal attention remains scant (Servais et al., 2023 for a recent review; see also Benedek et al., 2017; Korda et al., 2023; Walcher et al., 2017). As such, it remains an open 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 the cue, we analyzed the P1, P2 and CNV components. For the target, we focused our analysis on the P1, N1, and P2 components. 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). At the cue level, we expected early visual attention effects during the processing of the cue, based on our previous findings (Verschooren, Schindler, et al., 2021). However, it is currently unclear whether these early attention effects depend on the direction of the switch, as this was not possible to determine in this previous study. In addition, if perceptual decoupling occurs during target processing on internal trials, we would expect reductions in the P1-N1 complex there, reflecting reduced sensory processing (see Kam & Handy, 2013, for a review). Finally, it is on open question whether asymmetrical activity would be most outspoken during cue or during target processing, which is informative with regards to the presence of preparatory reconfiguration of attention versus attentional shielding processes (see Schmitz & Voss, 2012, 2014), as we examine in the Discussion section.

Figure 1.

Switching Attention Task.



Note. 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 (300-500ms), followed by the presentation of the cue ('E' and 'I' for external and internal trials, respectively) for 1000ms, after which the targets appeared on screen until response or for 200ms. 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).

2. Material and Methods

2.1. 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), but did not run a formal power analysis. We collected a larger sample and utilized a less complex design than this previous study, however. 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 1 participant for a technical error during data collection, 36 remained in the final sample.

2.2. Method

2.2.1. Materials

We used 16 stimuli from a stimulus set of non-verbalizable black line drawings (Endo et al., 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 off-line 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 by 600 pixels) in squares (100 by 100 pixels) equidistant from the center of the screen in a 2x2 array, with the probe (100 by 100 pixels) appearing centrally.

2.2.2. 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 60cm away from a 19′ inch 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. 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 2x2 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 milliseconds, 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 seconds, or until response. After each trial, feedback was provided in Dutch ('Correct!', 'Error!', 'Too late') for 1 second, 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 milliseconds, 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 seconds or until a response was given. Feedback was provided in Dutch for 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 milliseconds, after which a cue was presented for one second, 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 2x2 array. Simultaneously, the target location would be selected with a blue frame and the central probe appeared. The stimuli remained on screen for 2 seconds or until a response was provided.

The main experiment consisted of one practice block and eight experimental block, 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 pseudo-randomized to ensure that each 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'-key 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 x 2 design. After removing the practice block trials and the two warm-up trials at the start of each block, this resulted 160 trials per cell of the design.

2.2.3. 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 (CMS) and a Driven Right Leg passive electrode (DLR). 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). Additionally, 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 downsampled the signal from 512 Hz to 250 Hz. For each trial, epochs were selected for the cue and target separately. For the cue, these epochs were selected from 200 milliseconds before onset until 1000 milliseconds after onset. For the target, these epochs were selected from 200 ms before onset until 600 milliseconds after onset. Epochs for error trials and trials following an error trial were removed. To fit the independent components analysis (ICA), we used a more highly filtered version of the data (between 1 Hz 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. This automatic selection was manually inspected and corrected where necessary. Following the ICA, we implemented autorejection algorithm (Jas et al., 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, the bad channels were interpolated (0 channels: N = 25, 1 channel: N = 5; 2 channels: N = 5, 3 channels: N = 1) and re-referenced the data to the average of all electrodes. Overall, 10.17% (SD = 25.42%) of all epochs were removed. 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.

2.3. Data analysis

2.3.1. 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 reaction time that was faster than 150ms. 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, choosing 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).

As a next step, we tested the hypothesis that there is a cost associated with switching compared to repeating, and whether 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 (GLMM).

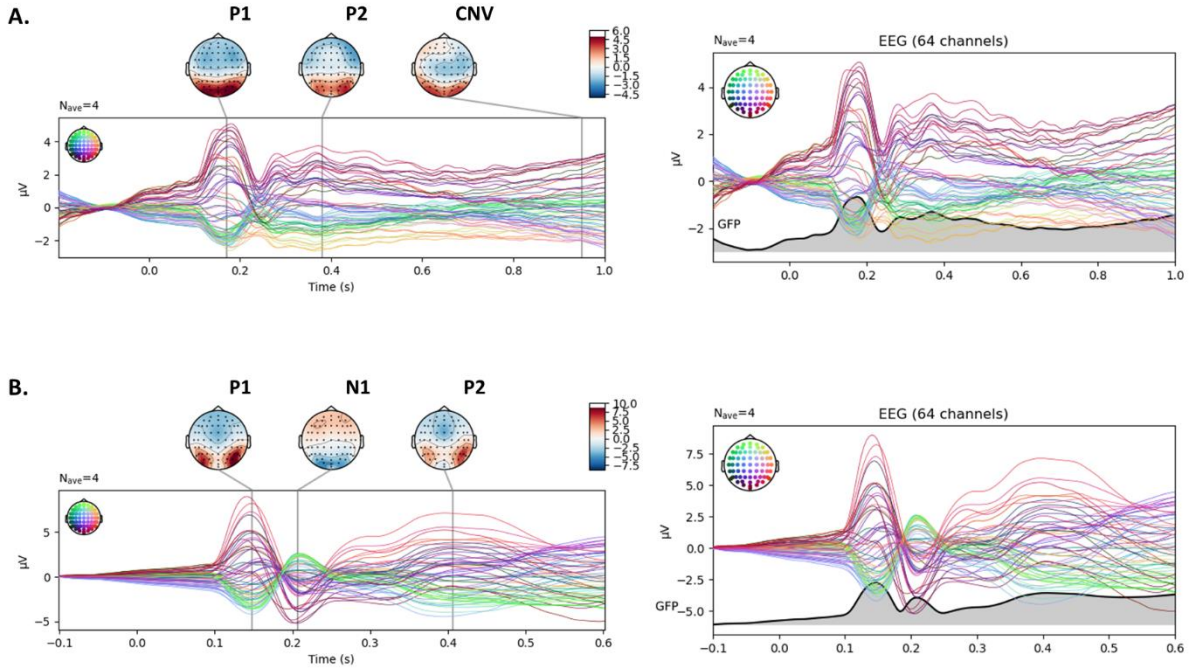
2.3.3. ERP analysis

We selected electrodes and time-windows based on a collapsed localizer approach (Luck & Gaspelin, 2017; see **Fig. 2**). For the cue-locked components, we selected electrode O1, O2, PO7, and PO8 for the P1 and P2 components and electrode Cz, FCz, C2, FC2, FC4, and FC6 for the CNV component. For the target-locked components, we selected electrode PO8, P8, PO7, and P7 for the P1 component, electrode O1, O2, Oz, and POz for the N1 component, and electrode O1, O2, Oz, POz, Iz for the P2 components. For the P1 and N1 components (both cue and target), we averaged the mean amplitude for the selected electrodes over a time window of approximately 20ms (i.e., the closest approximation in samples) around the peak

amplitude. For the cue-locked P1 component, we observed a biphasic peak, for we include an additional analysis in the supplementary materials in which we accommodate for this biphasic peak by scoring each peak separately. For the P2 and CNV component, we averaged the mean amplitude for the selected electrodes over a time window of approximately 100ms around the peak amplitude. We used these mean values for each subject in a Repeated Measures Analysis of Variance for each component of interest, testing for the main effects and interactions between Attention Type and Switch Type.

Figure 2.

Collapsed localizer and global field potential



Note. A. Collapsed localizer (left panel) and the global field potential (right panel) 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.

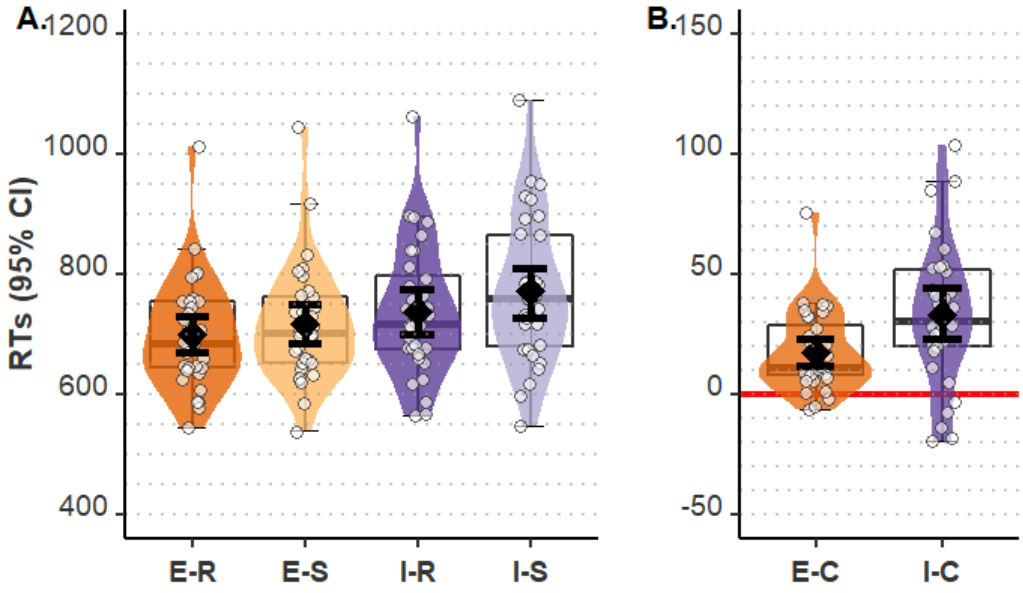
3. Results

3.1. Behavior

The analysis of the RT data revealed main effects for Attention Type (B = -0.03, t = -21.0, p < 0.001) and Switch Type (B= -0.2, t = -12.2, p < 0.001). Participants were slower on internal compared external trials and on switch compared to repetition trials (see **Fig. 3A**). In addition, the interaction between these two factors was significant (B = 0.01, t = 3.7, p < 0.001). Transformed back to the original response scale, the model estimate for the external switch cost was 17ms (95% CI = [10;24]) and for the internal switch cost it was 34ms (95% CI = [26;41]; see **Fig. 3B**). The model for the ER data showed a significant effect for Attention Type only (B = 0.13, t = 5.4, p < 0.001). 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 3.

Reaction Times



Note. A. Reaction times (95% CI) for each condition separately (E-R: external-repetition; E-S: external-switch; I-R: internal-repetition; I-S: internal-switch). B. Switch cost for each Attention Type (E-C: external cost; I-C: internal cost).

3.2. ERP analysis

3.2.1. Cue

3.2.1.1. P1

The Repeated Measures Analysis of Variance showed a main effect for Switch Type ($F_{1,35}$ = 5.30, p = 0.027, η_p^2 = 0.13), with higher amplitudes for repetition compared to switch trials. There was no effect of Attention Type ($F_{1,35}$ = 0.85, p = 0.364, η_p^2 = 0.02), but the interaction between Attention Type and Switch Type was significant ($F_{1,35}$ = 4.86, p = 0.034, η_p^2 = 0.12; see **Fig. 4A**). More specifically, the P1 amplitude was smaller on external-switch than external-repetition trials (d = 0.76, t = 2.95, p_{holm} = 0.029, Cohen's d = 0.27) while for internal trials, this difference was not observed (d = 0.28, t = 1.08, p_{holm} = 0.86, Cohen's d = 0.10). It should be noted, however, that the P1 peak for external trials was biphasic, with an early and a later peak, for both repetitions and switches (see Discussion section).

3.2.1.2. P2

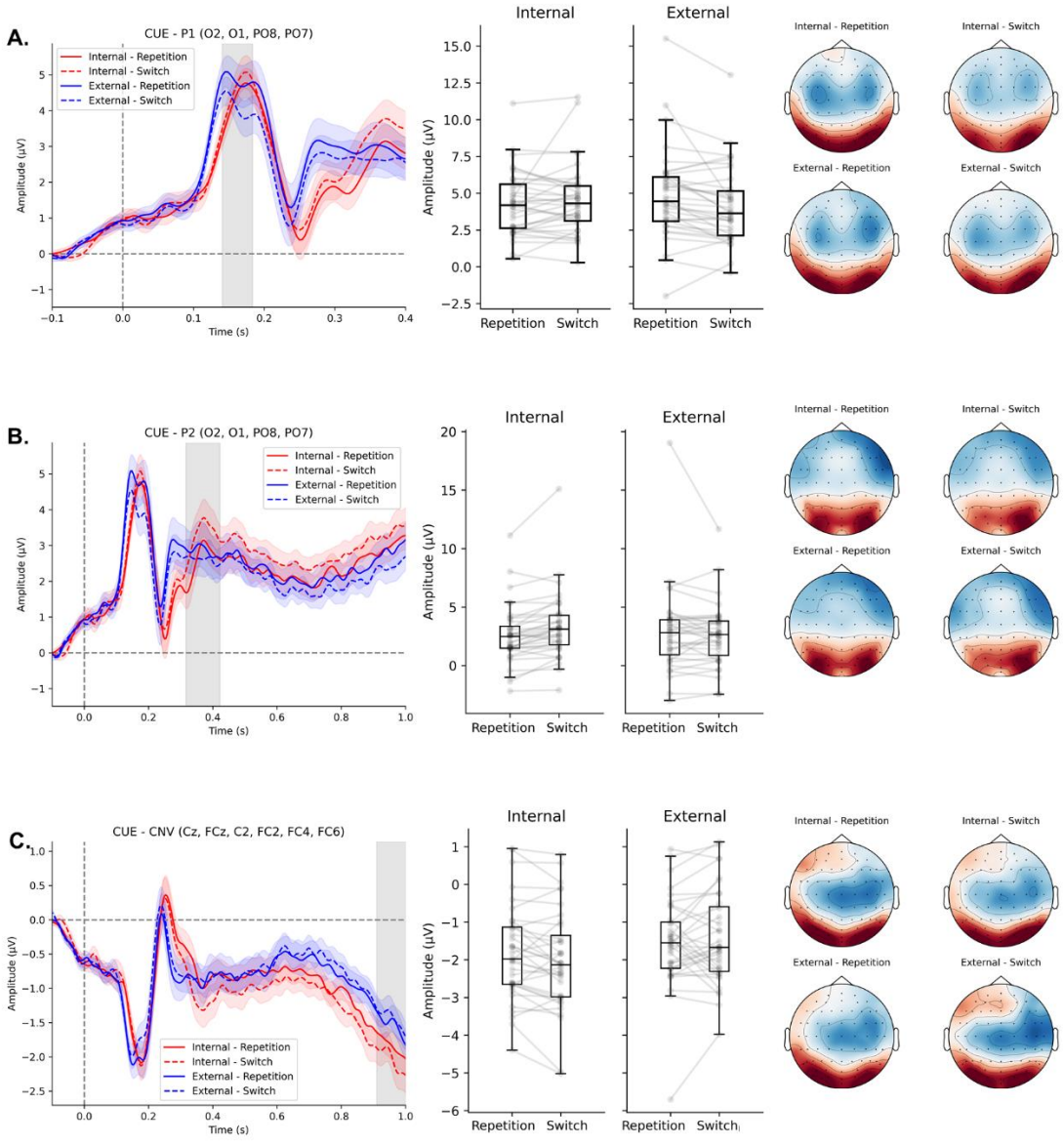
For the cue-locked P2, the main effect of Switch Type was significant ($F_{1,35}$ = 5.15, p = 0.03, η_p^2 = 0.13), but not of Attention Type ($F_{1,35}$ = 1.19, p = 0.18, η_p^2 = 0.05). The interaction between both effects was significant, however ($F_{1,35}$ = 6.05, p = 0.02, η_p^2 = 0.15; see **Fig. 4B**): while the P2 amplitude was significantly smaller on internal-repetition trials than on internal-switch trials (d = 0.69, t = 3.24, p_{holm} = 0.013, Cohen's d = 0.23), this was not the case for external-switch compared to external-repetition trials (d = 0.24, t = 1.11, p_{holm} = 0.81, Cohen's d = 0.08).

3.2.1.3. CNV

The main effect of Attention Type was significant ($F_{1,35}$ = 17.16, p < 0.001, η_p^2 = 0.33), but not of Switch Type ($F_{1,35}$ = 0.56, p = 0.46, η_p^2 = 0.02) or their interaction ($F_{1,35}$ = 3.49, p = 0.07, η_p^2 = 0.09; see **Fig. 4C**).

Figure 4.

EEG results time-locked to the cue



Note. Cue-locked averaged ERP waves plotted over time (in μV, error bars representing within-subject 95% CI; left panel), 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 panel) for the P1 (A.), P2 (B.), and CNV (C.) components. for the P1 (A), P2 (C), and CNV (C) components.

3.2.2. Target

3.2.2.1. P1

The main effect of Attention Type was significant ($F_{1,35}$ = 4.76, p = 0.036, η_p^2 = 0.12), but not of Switch Type ($F_{1,35}$ = 1.11, p = 0.30, η_p^2 = 0.03) or their interaction ($F_{1,35}$ = 1.40, p = 0.25, η_p^2 = 0.04; see **Fig. 5A**).

3.2.2.2. N1

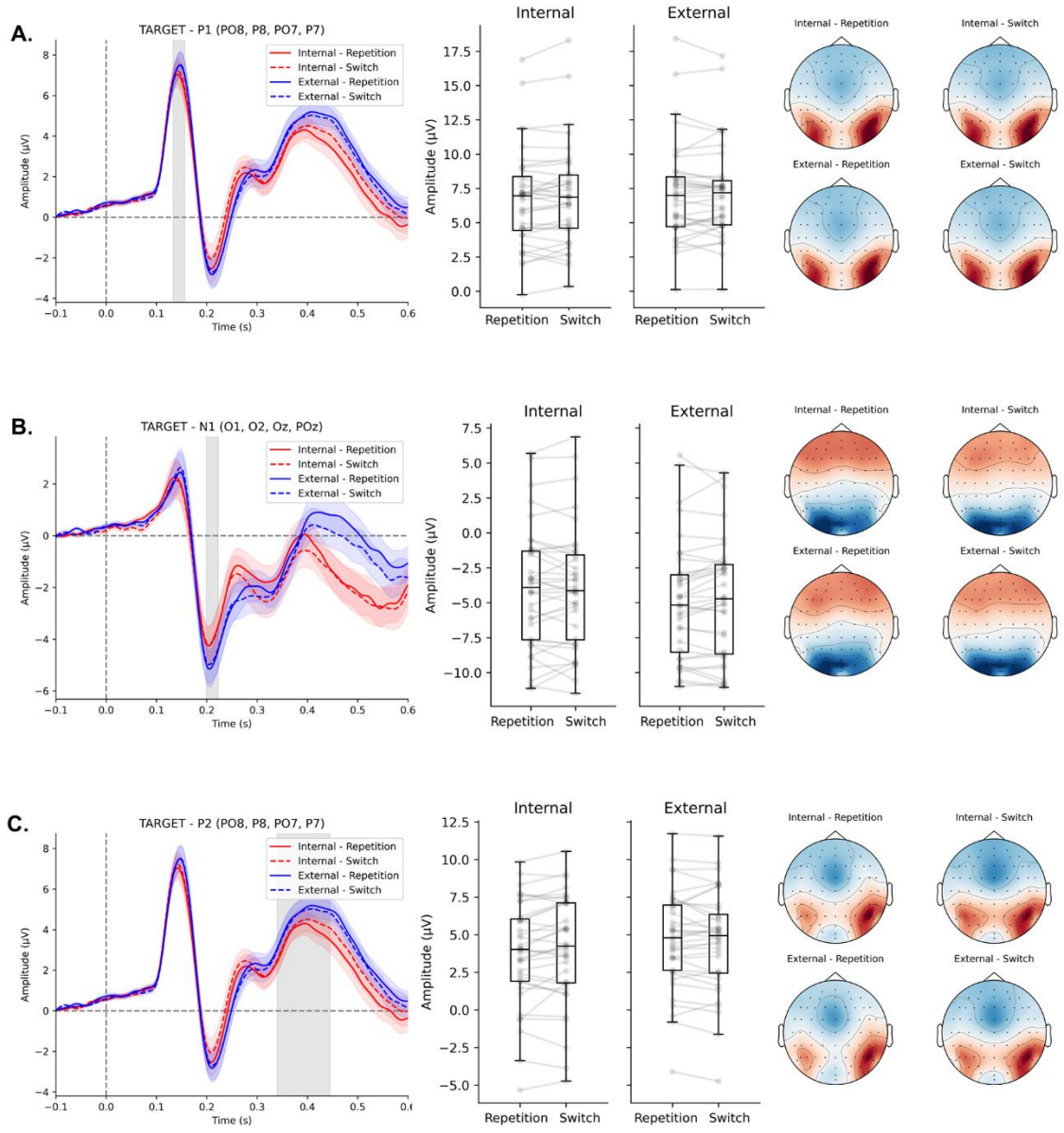
For the target N1, there was a significant main effect of Attention Type ($F_{1,35}$ = 11.55, p = 0.002, η_p^2 = 0.25), but not of Switch Type ($F_{1,35}$ = 0.40, p = 0.53, η_p^2 = 0.01) or their interaction ($F_{1,35}$ = 0.35, p = 0.56, η_p^2 = 0.01; see **Fig. 5B**).

3.2.2.4. P2

For the target-locked P2, we found a main effect of Attention Type ($F_{1,35}$ = 10.51, p = 0.003, η_p^2 = 0.23), but no main effect of Switch Type ($F_{1,35}$ = 1.62, p = 0.21, η_p^2 = 0.04). We did find a significant interaction between Attention Type and Switch Type ($F_{1,35}$ = 8.00, p = 0.008, η_p^2 = 0.19; see **Fig. 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_{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_{holm} = 0.30, Cohen's d = 0.04).

Figure 5.

EEG results time-locked to the target



Note. Target-locked averaged ERP waves plotted over time (in μV, error bars representing within-subject 95% CI; left panel), 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 panel) for the P1 (A.), P2 (B.), and CNV (C.) components. for the P1 (A), P2 (C), and CNV (C) components.

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 when and during which processing stage the cost asymmetry would be most outspoken, which is difficult to do with purely behavioral data. 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 (Hautekiet et al., 2023; Verschooren, Liefooghe et al., 2019; Verschooren, Pourtois, et al., 2020; Wang et al., 2024).

Our EEG results revealed three different stages of processing during these switches. First, time-locked to the 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 towards internal trials compared to 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 to 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 to 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 to external trials. The CNV component tracks a variation of cognitive and motivational factors, most notably motor preparation and stimulus anticipation (Brunia, 1988; van Boxtel & Brunia, 1994). In the current context, this CNV amplitude difference specifically reflects the difference in preparation between external and internal trials. Increased CNV amplitudes on internal trials indicate that participants exhibited 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, i.e., whether the current trial repeated or switched between attention state of the previous trial, which implies that this process is non-specific. One interpretation of this non-specificity 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 to internal repetition trials. An interesting avenue for future research would be to target the CNV specifically to determine whether such an interaction might occur under different conditions.

In addition, we found an interaction effect for both the P1 and P2 component time-locked to the cue. For the P1, we found a larger reduction in amplitude when switching towards external trials, compared to 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). The absence of this effect on internal trials might be related to the perceptual decoupling process, i.e., a processing delay due to attention being drawn internally, in line with the later CNV effect. Due to the biphasic nature of the P1 peak on external trials specifically (see **Fig. 2A**), however, it is challenging to clearly interpret the findings. We also found an interaction effect for the P2 component, with an increase in amplitude for internal switch trials compared to internal repetition trials, which was absent for the external trials. This effect might represent a compensatory process for the absence of an effect at the P1 level. This remains to be investigated in future, targeted research as well.

In sum, 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 to 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 et al., 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 that showed that attention is already drawn inward before (internal) target onset. 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 non-attended stimuli (Handy et al., 2001; Hillyard et al., 1998; Luck et al., 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). 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 common (see Verschooren & Egner, 2023), a point on which we elaborate below.

Taken together, the reduced amplitudes for the P1 and N1 components indicate 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. Curiously, however, there was no interaction effect for the P1 or N1 component, which would map onto the switch cost asymmetry. To explain the cost asymmetry, 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 provided evidence for an interaction effect for the P2 component, which had a similar signature as the asymmetrical costs found at the behavioral level: the P2 showed a reduction on internal repetition compared to 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, we can straightforwardly explain the cost asymmetry at the behavioral level: 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 indication 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 et al., 2018), suggestive of perceptual decoupling, others have actually found an increase in the P2 component during mind wandering (e.g., Braboszcz & Delorme, 2011; Compton et al., 2024). 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, while 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 trials compared to 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 to 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 to repetition trials, which would also signify enhanced internal attention. While 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 to repetition trials due to ineffective perceptual decoupling.

In sum, the interaction effect for the P2 component, with an increased amplitude on internal switch compared to internal repetition trials, most likely reflects a disrupted perceptual decoupling process. 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 re-engaged. For external trials, no such process took place. While the P2 component is not often interpreted in terms of perceptual decoupling in the mind-wandering literature, our current results suggest that it might reflect this decoupling process in the context of selective internal attention. In the next section, we bridge this finding with existing behavioral accounts 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 we learned 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, i.e., 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 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 straightforward to decouple external attention from internal sources of information, which has some face validity, as we always rely to some degree or another on previously encoded information.

As a side note, there is another way in which our new ERP findings are compatible with an internal shielding benefit, which derives from the associative interference account. The associative interference account predicts that the activity contributing to the cost asymmetry would occur most strongly when the stimulus appears, as this is the moment the conflicting attentional settings are activated by the task context, rather than during the preparation before stimulus onset. This is important, as an alternative attentional flexibiltiy account, the priming account, predicts that the asymmetry stems from asymmetries in carry-over (and inhibition) of the attentional setting (see also Schmitz & Voss, 2012, 2014). Carryover of attentional settings is sensitive to effects of preparation time during the cue-target interval (CTI). As such, if priming or carryover of the attentional settings played a role in the cost asymmetry, we would expect most asymmetrical activity during the CTI, rather than following target onset. The fact that we have found asymmetrical activity time-locked to the target, rather than to the cue, thus provides further evidence for the compatibility between these results and the associative interference account, which implies an internal shielding benefit.

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 (IDEA) 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, while 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). Crucially, this IDEA 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 hypothesis by providing a potential mechanism for how attention can be drawn inward and protected from irrelevant or non-urgent external interference.

Conclusions

We discovered 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, which became asymmetrical for the P2 component. This perceptual decoupling mechanism underlies the behavioral cost asymmetry and can help explain the internal shielding benefit, which has broad implications for the overall balance between external and internal attention.

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 Contribution Section

SV: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Visualization; LV: Formal analysis, Data Curation, Visualization; SB: Investigation; GP: Conceptualization, Writing - Review & Editing, Supervision, Funding acquisition

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