

Orienting attention to visual or verbal/auditory imagery differentially impairs the processing of visual stimuli



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ABSTRACT

When attention is oriented toward inner thoughts, as spontaneously occurs during mind wandering, the processing of external information is attenuated. However, the potential effects of thought's content regarding sensory attenuation are still unknown. The present study aims to assess if the representational format of thoughts, such as visual imagery or inner speech, might differentially affect the sensory processing of external stimuli. We recorded the brain activity of 20 participants (12 women) while they were exposed to a probe visual stimulus in three different conditions: executing a task on the visual probe (externally oriented attention), and two conditions involving inward-turned attention i.e. generating inner speech and performing visual imagery. Event-related potentials results showed that the P1 amplitude, related with sensory response, was significantly attenuated during both task involving inward attention compared with external task. When both representational formats were compared, the visual imagery condition showed stronger attenuation in sensory processing than inner speech condition. Alpha power in visual areas was measured as an index of cortical inhibition. Larger alpha amplitude was found when participants engaged in an internal thought contrasted with the external task, with visual imagery showing even more alpha power than inner speech condition. Our results show, for the first time to our knowledge, that visual attentional processing to external stimuli during self-generated thoughts is differentially affected by the representational format of the ongoing train of thoughts.

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1. Introduction

Attention allows enhanced processing of attended spatial location, visual features, or sensory modalities while suppressing the ignored ones (Foxye and Snyder, 2011; Hillyard et al., 1998; Nobre and Kastner, 2014; Payne et al., 2013; Posner, 1980; Snyder and Foxye, 2010; Spence et al., 2001). Studies on bimodal selective attention (visual/auditory) have shown that attention to one sensory modality led to increased activity in relevant sensory cortices while simultaneously leading to decreased activity in irrelevant sensory cortices (Johnson and Zatorre, 2005, 2006). These studies give support to the hypothesis that attention would be mediated by supramodal control processes (Eimer and Van Vezzen, 2002; Farah et al., 1989) or at least separable-but-linked attentional systems (Spence and Driver, 1996). An interesting question is how these supramodal control processes operate when attention is internally oriented.

A ubiquitous phenomenon in which attention is internally oriented to self-generated mental activity is known as mind wandering (Smallwood and Schooler, 2006). Most studies have approached mind wandering as a

unitary “off-task” attentional state, which is compared with an “on-task” condition (Baird et al., 2014; Braboszcz and Delorme, 2011; Kam et al., 2012, 2011; Smallwood et al., 2008). This “off-task” conception of the mind wandering phenomenon has given rise to the concept of perceptual decoupling (Schooler et al., 2011; Smallwood and Schooler, 2006) proposed as a mechanism to suppress incoming external information in order to maintain the internal train of thoughts. This disengagement of attention from perception would entail an interference with ongoing tasks and has been supported by electrophysiological evidences showing a reduction in external stimuli attentional processing at both cognitive and early sensory level in visual and auditory modalities (Braboszcz and Delorme, 2011; Kam et al., 2011; Smallwood et al., 2008). This evidence of generalized attentional suppression of sensory cortices during internally oriented attention is suggestive of a re-allocation of the same attentional processes used to attend to different sensory modalities.

However, a still unknown aspect about this phenomenon is whether different mental contents can differentially affect the brain dynamics and sensory processing, which is difficult to answer from the “off-task” perspective. Recently, there has been a growing interest regarding the phenomenological dimensions of this process (Killingsworth and Gilbert, 2010; Poerio et al., 2013; Ruby et al., 2013; Stawarczyk et al., 2013, 2011; Tusche et al., 2014). One of these is known as the “representational format of thoughts,” which involves the visual imagery and the inner speech. Some studies have approached this dimension

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(Andrews-Hanna et al., 2013; Gorgolewski et al., 2014), stressing the diversity of self-generated thoughts and the potential impact that thought's content may have on the underlying brain dynamics, but no attempt to assess its potential attentional effects on sensory processing of external information has been made so far.

Previous research has shown that visual imagery and visual perception share specialized, specific mechanisms (Kosslyn et al., 2001). Results have even shown that visual imagery activates the same areas that visual perception in the early visual cortex (Sereno et al., 1995; Tootell et al., 1998). On the other hand, neuroimaging studies have shown that during inner speech, the same brain regions related to auditory language processing are activated, but visual areas show no activation (McGuire et al., 1996; Shergill et al., 2001).

These evidences strongly suggest that thoughts use different cortical processing resources depending on their representational format, which might impair the attention to external stimuli if they use the same sensory modality.

The present study aims to assess whether the representational format of thought differentially influences the attenuation of sensory response to visual stimuli. For this purpose, we designed an experiment in which participants were instructed to count visual probes (an external task) while in other two conditions they were instructed to think about whatever they wanted but constraining their thoughts to a visual imagery format or an inner speech format. These last two are also task-based conditions as thought's onset is triggered by an imperative stimulus which also indicates the thought's representational format. This task-based design allows overcoming the methodological challenges often faced by classical studies on mind wandering e.g. we can know more accurately the onset, timing, and the content's category of the self-generated mental activity.

We compared electrophysiological responses to visual stimuli when they are attended and when they are not preferentially attended because participants were engaged in either auditory inner speech or visual imagery. Early components of event-related potentials (ERPs) and posterior alpha band were measured as they have been reported to reflect early visual sensory processing and attention allocation (Eimer, 2014; Schroeder et al., 2014; Shapiro and Hanslmayr, 2014). Specifically, we hypothesized that when participants are involved in visual imagery, they would exhibit a diminished sensory response to external visual stimuli compared to when they are engaged in a process of inner speech.

2. Methods

2.1. Participants

Twenty-six volunteers initially participated in this study. Because of excessive ocular/muscular artifacts and problems in data acquisition, six subjects were rejected for further analysis. Thus, the results from twenty subjects (12 women) are reported here (mean age = 24.43, range = 19–33). All participants had normal or corrected-to-normal vision and reported no color-vision deficiency. Participants gave informed consent and had no history of drug abuse, neurological or psychiatric conditions. The Ethics Committee of Pontificia Universidad Católica de Chile approved the study. All experiments were performed at the Neurodynamic Laboratory of the School of Psychology of this University.

2.2. Stimuli and procedure

All stimuli were presented on a computer screen with gray background situated 57 cm away from the subject. Psychopy software (Peirce, 2007) was used to design and present the experiment. The task was composed of 2 blocks; each block had 30 auto-administrated trials. Before each block, participants were asked to fix their eyes on a fixation cross in the middle of the screen; they were also asked to reduce their blinking as much as possible. Participants started each trial by pressing a button; after this, either the word “imagine” or “speech”

came up in the middle of the screen (Fig. 1). Next, a red or green, 2 cm radius circle appears indicating whether the attention should be allocated in the external stimuli (red) or in their thoughts (green). After this, 10 square (sides were 3 cm) stimuli with a checkerboard pattern appeared sequentially. Each square was presented for 0.2 s and the pattern in them was inverted every 0.1 s from onset.

When the word “imagine” appears followed by the green circle, participants were instructed to think about anything they wanted, given that it had a strictly visual quality, avoiding auditory or phonological elements of any form. This condition will be referred to as “visual imagery.” If the word “speech” was followed by a green circle participants were instructed to think using their inner speech without using any sort of mental image. This condition will be referred to as “inner speech.” Finally, if any of the two words were followed by a red circle, participants were instructed to count 10 of the appearing square stimuli and mark the tenth square using the spacebar. This condition will be referred to as “external task.” Color cues were counterbalanced, i.e. during the second block, the red circle cued the thought-related tasks and the green circle cued the visual task.

2.3. Recordings

EEG data was obtained using 64 electrodes (Biosemi ® ActiveTwo) arranged according to the international 10/20 extended system. Horizontal and vertical eye movements were monitored using four external electrodes. Horizontal EOG was recorded bipolarly from the outer canthi of both eyes and vertical EOG was recorded from above and below of the participant's right eye. Two additional external electrodes were placed on the right and left mastoid to be used for later re-referencing.

2.4. Data pre-processing

Data pre-processing was performed using Matlab 7.8.0 (The Mathworks, Inc.) with EEGLAB v7.1.7.18b toolbox (Delorme and Makeig, 2004). The signal was down-sampled off-line at 512 Hz for ERP analysis and at 1024 Hz for frequency analysis. Because of hardware setup constraints, all electrodes were referenced to CMS and DRL during acquisition, but off-line re-referenced to averaged mastoids. Horizontal and vertical EOG were calculated by means of the difference between left–right electrodes and above–below electrodes, respectively. A 2nd-order infinite impulse response (IIR) Butterworth filter was used for band-pass filtering continuous EEG data, with a half-amplitude cut-off frequency of 0.1 Hz and 30 Hz for ERP analyses and a half-amplitude

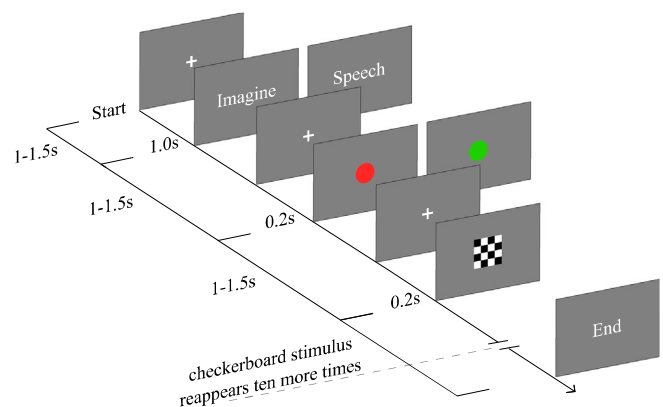


Fig. 1. Schematic of experimental paradigm. Each trial started by pressing a button triggering a fixation cross presented between 1 and 1.5 s. When the word “imagine” appears followed by the green circle, participants were instructed to think about any mental image, avoiding auditory elements. If the word “speech” was followed by a green circle, participants were instructed to think using only their inner speech. Finally, if any of the two words were followed by a red circle, participants were instructed to count 10 of the appearing square stimuli and mark the tenth square using the spacebar. Color cues were counterbalanced between blocks.

cut-off frequency of 0.1 Hz and 100 Hz for frequency analyses. Artifact detection was performed on segmented data (see below epoch extraction details) using a moving window peak-to-peak threshold algorithm, with a voltage threshold of 100 microvolts. Manual inspection was also performed in order to detect other artifacts like muscle activity. This was done in a manner that was blind to experimental condition. All detected artifacts were rejected.

2.5. ERP analysis

The EEG signal was segmented into 20 trials per conditions, each trial window captured from the appearance of the colored circle up to the trial's end. Further segmentation in epochs was applied for each condition, selecting the 200 ms preceding each checkerboard appearance up to 500 ms after that. All of the epochs corresponding to the first appearing checkerboard were discarded given that participants were less likely to have already engaged in a thought process. In the external task condition, the epochs corresponding to the last appearing checkerboard were discarded due to possible motor execution artifacts. The average number of epochs per participant was 113.1 (SE: 11.7) for the visual imagery condition, 110.45 (SE: 12.18) epochs for the inner speech condition, and 110.35 (SE: 12.45) epochs for the external task condition.

Epochs were averaged across trials for each subject and condition. The P1 peak was identified as the highest recorded voltage occurring in the 70–140 ms time window following a checkerboard stimulus. The N1 peak was defined as the lowest recorded voltage occurring in the 110–190 ms time window following a checkerboard stimulus. The PO7 and PO8 electrodes were used to find both the P1 and N1 components. The chosen latencies and topographical distributions of early components are described in previous research (Di Russo et al., 2002). We then calculated local peak amplitude for P1 and N1 component according to Steven J. Luck (2005), for each subject and condition.

The P300 amplitude was calculated as local peak amplitude in a time windows between 330 and 360 ms at Pz electrode. The N400 component was obtained at FCz and Cz electrodes, following the topographical distribution proposed by Kutas and Hillyard (1980). N400 amplitude was established for each subject and condition as the difference between the corresponding peak (an average of 10 ms around the maximum negativity between 370 and 480 ms) and a baseline calculated by averaging the 280–330 ms window following checkerboard stimuli.

2.6. Spectral frequency analysis

The following analysis used 1 s epochs free of any stimulus; these epochs were found from the appearance of the colored circle until the trial's end for every subject, trial and condition. The average number of epochs per participant was 101.25 (SE: 11.16) for the visual imagery condition, 100.45 (SE: 10.7) epochs for the inner speech condition, and 100.15 (SE: 10.65) epochs for the external task condition. Fourier spectrogram was calculated using an in-house script in MATLAB (The Mathworks, Inc). Occipital and parieto-occipital electrodes showed the greatest alpha power in scalp topography; in particular O1, O2, PO3, PO4, PO7, and PO8 were selected for further analysis following a data-driven criterion described in Keil et al. (2014).

Spectrogram data were averaged across epochs for each subject for the three conditions. Alpha range was defined as a window of 2 Hz above and 2 Hz below the maximum power value in the classical alpha range (8–12 Hz) for each subject (Klimesch, 1999). Area under the curve (AUC) of alpha power was calculated averaging alpha range for each subject. Relative power was calculated by dividing AUC alpha range by the total AUC.

2.7. Statistics

Local peak amplitude of P1 and N1 evoked by attentional checkerboard probes were compared with repeated-measures ANOVA using

Electrode (two levels: PO7, PO8) and Condition (three levels: visual imagery, inner speech, external task) as factors. P300 amplitudes were compared with repeated-measures ANOVA using Condition (three levels: visual imagery, inner speech, external task) as factor. N400 amplitudes were compared with repeated-measures ANOVA using Electrode (two levels: FCz, Cz) and Condition (three levels: visual imagery, inner speech, external task) as factors. Alpha power's AUC was compared with repeated-measures ANOVA using Hemisphere (two levels: right, left), Electrode (three levels: PO7/8, PO3/4, O1/2) and Condition (three levels: visual imagery, inner speech, external task) as factors.

ANOVA showed that at least one variable was different; in order to determine what conditions differed from each other, further analyses was done by applying an univariate test of significance for planned comparison.

For all repeated-measures ANOVA and planned comparisons, the effect size is reported using partial eta-squared value.

In all cases, Mauchly Sphericity Test was carried out, and Greenhouse–Geisser corrections were applied when necessary. All statistics were done using STATISTICA 7.0 software (StatSoft, Inc).

3. Results

3.1. Early components of visual ERP evoked by checkerboard stimuli

The main aim of ERP analyses in the present study was to investigate the effect of inner thought's representational format on early visual sensory response toward an external stimulus. For this purpose, we compared three attentional conditions, one in which participants perform an external visual task, one in which participants had to perform visual imagery, and a third condition in which they had to generate inner speech.

The early ERP components showed the classical scalp topography (Fig. 2A). The ERP waveform elicited by checkerboard stimuli at parietal-occipital region (average of PO7 and PO8 electrodes) is shown in Fig. 2B for the three conditions. Statistical analysis for P1 amplitude revealed a main effect for the condition factor, $F(1, 38) = 6.503$, $p = 0.003$, $\eta^2_{\text{partial}} = 0.255$. A further analysis was carried out with planned comparisons, revealing a stronger amplitude attenuation for inner speech compared with visual imagery condition ($F(1, 19) = 4.98$, $p = 0.037$, $\eta^2_{\text{partial}} = 0.207$) and for external task with visual imagery ($F(1, 19) = 7.89$, $p = 0.011$, $\eta^2_{\text{partial}} = 0.293$). Inner speech condition also showed a weaker but significant attenuation contrasted with external task ($F(1, 19) = 4.71$, $p = 0.042$, $\eta^2_{\text{partial}} = 0.199$) (Fig. 2C). N1 amplitude shows no differences between conditions ($F(1.87, 35.65) = 2.71$, $p = 0.082$).

These results show that there is a reduction in sensory response to external visual stimuli when attention is oriented to self-generated thoughts such as it has been shown in previous studies. However, our results also show differences related with a phenomenological dimension of thoughts. Specifically, we show that visual sensory processing is more significantly attenuated when attention is oriented to visually represented thought than when attention shifts to an inner speech thought.

3.2. P300 component evoked by checkerboard stimuli

In order to evaluate possible effects at later stages of cognitive processing, we assessed the P300 component in the time windows and scalp location where this component has been classically observed. An increase in voltage can only be seen in the external task condition $F(2, 38) = 6931$, $p = 0.002$, $\eta^2_{\text{partial}} = 0.267$, peaking at 346 ms. This is not observed in the conditions involving inward attention (see Fig. 3 in Data in Brief article; (Villena-González, López, & Rodríguez, submitted for publication)).

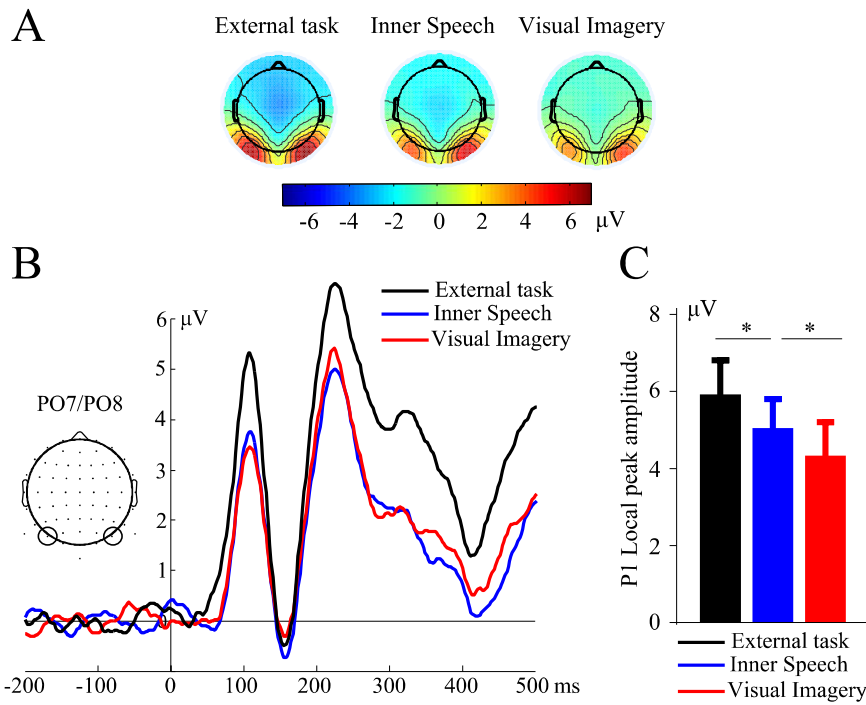


Fig. 2. Amplitude and topography of early P1 component. A) Voltage scalp topography during the P1/N1 time window for the three conditions. B) Grand average ERP waveform at PO7/PO8 electrodes for the three conditions. C) Mean and standard error of local peak amplitude of P1 component for the three conditions ($^*p < 0.05$).

3.3. N400-like component evoked by checkerboard stimuli

Around 400 ms after checkerboard appearance, a central and fronto-central negativity can be seen, slightly lateralized to the right hemisphere for the inner speech condition (Fig. 3A). This topography and timing are related with N400 component as classically described

(Kutas and Hillyard, 1980). The amplitude of this N400-like component at FCz/Cz electrodes was compared between the three conditions (Fig. 3B). There was a main effect for the condition factor, $F(2, 38) = 7.126$, $p = 0.0023$, $\eta^2_{\text{partial}} = 0.272$. Only the inner speech condition showed an increase in the amplitude of N400-like negativity while it was the same for the visual imagery and the external task conditions (Fig. 3C).

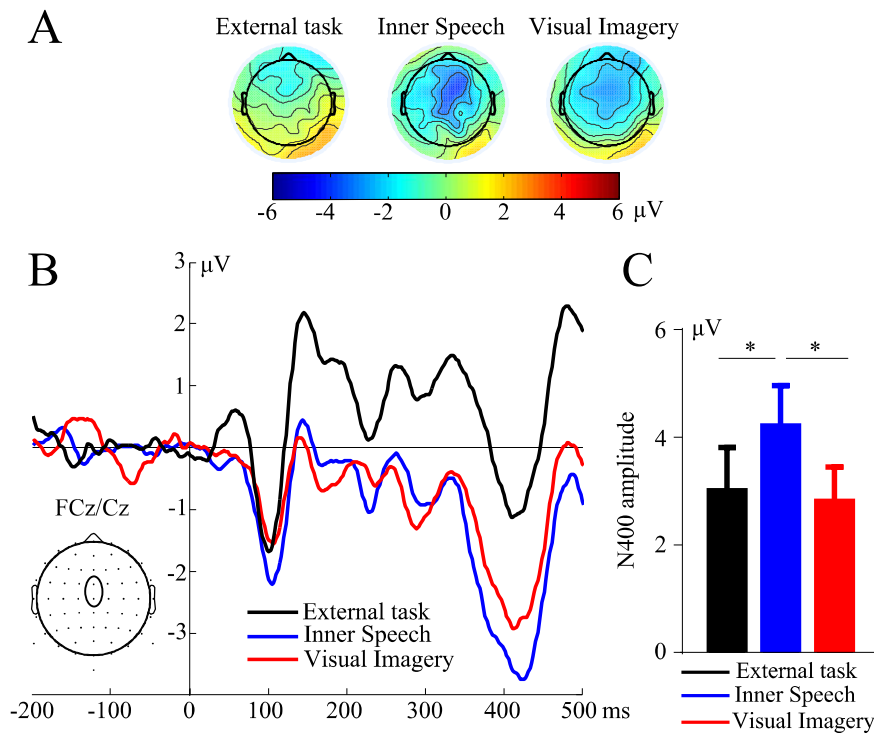


Fig. 3. Amplitude and topography of late N400 component. A) Scalp topography around 420 ms after stimulus onset for the three conditions. B) Grand average ERP waveform at FCz/Cz electrodes for the three conditions. C) Mean and standard error of N400 amplitude for the three conditions ($^*p < 0.05$).

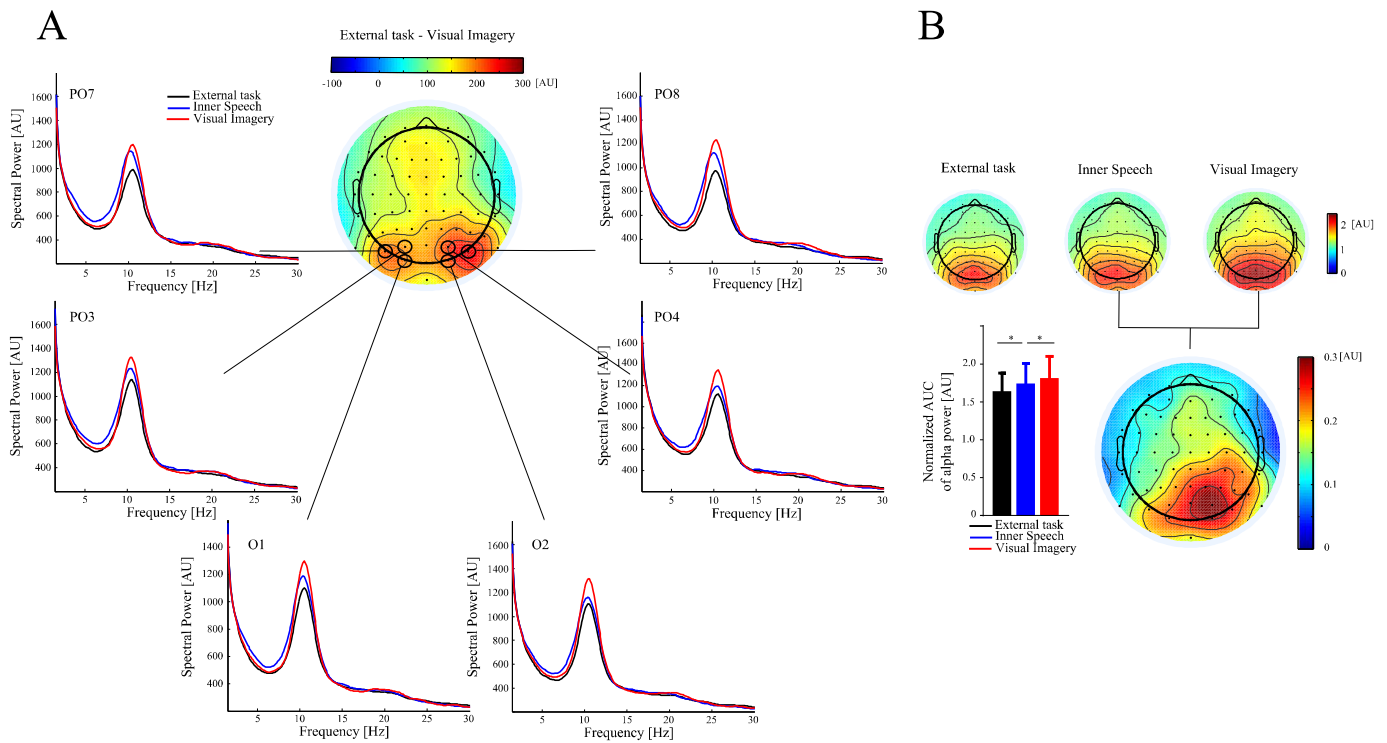


Fig. 4. Scalp topography and mean values of alpha band power. A) Scalp topography of the difference in alpha power between visual imagery and external task condition. Spectral power at parietal–occipital and occipital electrodes for the three conditions is shown. B) Scalp topography of alpha power for the three conditions (upper). Means and standard errors of alpha power's AUC for the three conditions ($*p < 0.05$) (lower, left). Scalp topography of the difference in alpha power between visual imagery and inner speech condition (lower, right).

3.4. Spectral alpha power results

We compared area under the curve (AUC) of alpha power for the three conditions. The topographic distribution of alpha power differences are restricted to occipital and parieto-occipital electrodes as can be seen in Fig. 4. There is an evident increase in alpha power for the two inward attention conditions contrasted to external task. However, this increase was larger for visual imagery condition than for inner speech condition as can be observed in Fig. 4A for all electrodes analyzed. Statistical analysis showed a main effect for condition, $F(2, 38) = 11.697$, $p = 0.00011$, $\eta^2_{\text{partial}} = 0.381$. Mean values of alpha power are shown in Fig. 4B for the three conditions. Planned comparison showed differences between external task and inner speech conditions, $F(1, 19) = 6.157$, $p = 0.022$, $\eta^2_{\text{partial}} = 0.244$ as well as between external task and visual imagery, $F(1, 19) = 26.578$, $p = 0.000056$, $\eta^2_{\text{partial}} = 0.583$. Furthermore, differences were also found between both representational formats, $F(1, 19) = 4.734$, $p = 0.042$, $\eta^2_{\text{partial}} = 0.199$. Differences in alpha power between both inward oriented attentional states are slightly right lateralized on scalp topography (Fig. 4B).

These results showed that there is an increase of occipital and parieto-occipital alpha power when attention is oriented to self-generated thoughts compared with external task. Additionally, differences can be observed between two inward attention tasks. Specifically, alpha power over parieto-occipital regions showed greater activity during visual imagery than during auditory/verbal imagery.

4. Discussion

We investigated the visual sensory response under different attentional conditions; one in which attention was directed to the visual task at hand, and another in which attention was focused on inner thoughts. This last condition was further divided into two different representational formats; inner speech and visual imagery. We hypothesized that when the participants are involved in visual imagery, they

would have a reduced sensory response to external visual stimuli compared to when their thoughts had been in the form of inner speech.

In line with previous studies showing an attenuation in sensory and cognitive processing of external stimuli during mind wandering (Baird et al., 2014; Barron et al., 2011; Kam et al., 2011; Smallwood et al., 2008), we found a reduction of brain processing at early and late stages during tasks that involved attending internally. These findings are consistent with the perceptual decoupling hypothesis (Smallwood and Schooler, 2006). The results showed that when attention is oriented inward, decoupling occurs regardless of the content of the thought.

Regarding the hypothesis of the present study, our main results showed that early sensory response to a visual stimulus is significantly attenuated in the visual imagery condition compared to the inner speech condition. Furthermore, occipital alpha power in the parieto-occipital regions was higher during visual imagery condition than during the inner speech condition, suggesting greater cortical inhibition when visual imagery was performed. Additionally, an N400-like component was found as a larger negativity for the inner speech condition than for the two other conditions, confirming the differential nature of this representational format. These results showed that the content of thoughts can differentially affect the processing of external information, suggesting that certain aspect of decoupling depends on modality-specific process. Specifically, thoughts represented as a visual imagery would impair visual processing of incoming inputs to a greater extent than thoughts represented as auditory inner speech, mainly due to competition for visual processing resources. In the following subsections, we discuss some important points raised by these results.

4.1. Visual processing attenuation during internally oriented attention

In the present study, we showed that the visual P1 component is reduced during both self-generated thought tasks compared to an external task condition.

Studies assessing visuo-spatial attention have shown P1 amplitude reduction when attention is not allocated where stimulus appear. For

this reason, P1 amplitude attenuation has been classically associated with reduced sensory processing of stimuli due to ignoring a visual field in which stimuli appear (Hillyard and Anllo-Vento, 1998; Hillyard et al., 1998; S. J. Luck and Hillyard, 1995; Mangun and Hillyard, 1988). This visual P1 amplitude attenuation has also been shown when attention is allocated to a different sensory modality (Eimer and Driver, 2000). In the context of mind wandering, studies have shown that during this “off-task” attentional state, there is a reduction in early visual P1 component compared to when attention is externally oriented (Baird et al., 2014; Kam et al., 2011). In a general view, the reduction of early components of ERPs has been understood as a reduction in sensory processing because attention has been allocated elsewhere (Eimer, 2014). It has been proposed that mind wandering involves shifting attention from external demands toward self-generated thoughts, unrelated to the task. The hypothesis called “perceptual decoupling” proposes that attention becomes decoupled from perception of external events (Smallwood and Schooler, 2006). Accordingly, attention to all external stimuli becomes attenuated since it is focused on internal information.

Additionally, our results showed an increase in spectral alpha power during both tasks involving internal self-generated thoughts compared with external attention. Alpha power has been classically associated with cortical inhibition. Specifically, alpha power increase is often related with diminished cortical excitability, and this can occur with open eyes by default network activation (Mo et al., 2013), by attentional suppression of visual features (Snyder and Foxe, 2010) or ignoring the visual field in which a stimulus appear (Cosmelli et al., 2011; Kelly et al., 2006; Worden et al., 2000). For this reason, alpha increase has been proposed as an index of cortical attentional suppression (Foxe and Snyder, 2011; Schroeder et al., 2014). Furthermore, previous research has already linked enhancements in alpha activity with internally oriented brain states (Cooper et al., 2003; Hanslmayr et al., 2011). Our results are in line with these studies.

Finally, in the present study, a positive deflection wave with a posterior distribution peaking at 346 ms was observed, but only during the external task condition. The absence of this component in the inward attention conditions might well reflect a reduction in the cognitive processing of the stimuli. Previous studies about mind wandering have shown P300 amplitude attenuation during these off-task states contrasted with on-task attentional states, those results have been interpreted as a cognitive processing reduction of external stimuli (Barron et al., 2011; Smallwood et al., 2008). In the case of the current study, the methodological approach allowed us to accurately know the participants' attentional state and its timing, which strongly support prior interpretations concerning the P300 component. Nevertheless, this result might also be interpreted as a process of “context updating” of working memory since visual stimulus was behaviorally relevant only during external task (Donchin, 1981; Polich, 2007). Further investigation would be needed, perhaps using attentional probes independent from the task-related targets.

In summary, our results show that when attention is reoriented toward a self-generated thought, there is a reduction in sensory processing of visual external stimuli. Besides, visual cortical inhibition, indexed by alpha power increase, also accompanied the internal train of thoughts. Previous studies have suggested that perceptual decoupling occurs when attention spontaneously shifts toward internal thoughts to stabilize and maintain thinking (Smallwood, 2013a; Smallwood and Schooler, 2006, 2015). In line with this, the current study suggests that the same occurs when attention is intentionally engaged on a self-generated thought.

4.2. Representational format of thoughts differentially impair visual attentional processing

Mind wandering has usually been studied as an “off-task” state, which is compared with another mental state in which attention is allocated to an external task. Several studies have tried to rescue some

phenomenological dimensions of this process, such as temporal orientation (Baird et al., 2011; Stawarczyk et al., 2013; Stawarczyk et al., 2011), emotional valence (Killingsworth and Gilbert, 2010; Poerio et al., 2013; Ruby et al., 2013; Tusche et al., 2014), and other dimensions such as self-relevance, level of meta-awareness, deliberateness, and representational format (Andrews-Hanna et al., 2013; Christoff et al., 2009; Gorgolewski et al., 2014; Seli et al., 2014). This last dimension might differentially impact in the processing of external information, and previous researchers have given valuable information about brain activation and functional connectivity during different forms to represent thoughts (Gorgolewski et al., 2014; Kosslyn et al., 2001; Shergill et al., 2001). Most importantly, it has been shown that visual perception and visual imagery share specialized brain areas while inner speech involves auditory, but no visual, language processing areas (McGuire et al., 1996; O'Craven and Kanwisher, 2000; Sereno et al., 1995; Shergill et al., 2001). Nevertheless, to our knowledge, no attempt to assess how the representational format of thoughts may potentially affect the sensory processing of external information has been made so far.

In the present study, we asked if representational format of thought differentially affects the brain's response to visual stimuli. We hypothesized that sensory processing of visual stimulus would be attenuated to a greater extent during a visual imagery than during inner speech because of processing resources competition.

The results of the present study show that when a subject performs visual imagery, the amplitude of early ERP's components (visual P1 components) is reduced compared with those obtained during the inner speech condition. As we discussed above, previous research has shown that early processing of external information is reduced when attention shifts toward self-generated thoughts. However, our results also show that differences in sensory processing can even be observed when two “off-task” states are compared. Specifically, a thought represented in the format of visual imagery reduces sensory processing of visual external information to a larger extent than a thought represented as inner speech.

Moreover, our results showed that when a visual imagery is performed, the alpha power in parieto-occipital regions is higher than during inner speech condition. This suggests that during visual imagery, there is a larger visual cortical suppression than in the other conditions. In summary, it seems that there might be a competition for processing resources between visual imagery and visual attention of external inputs, and this competition would not be present to the same extent if a thought is represented in a discursive format.

The negative ERP component observable at around 400 ms (N400-like) after the visual stimulus onset was, certainly, an unexpected result in the current study. The present experimental design was intended to measure early components of the visual ERP, but unsuitable to explore later and more specific components such as N400. Nevertheless, we found a negative deflection in the ERP time-locked to the probe stimulus. This negativity matched with a classical N400 on latency and topographical distribution, having larger amplitude only for inner speech condition. Classical N400 component is elicited by a violation of semantic expectations (Kutas and Hillyard, 1980). This has been shown by presenting a word or a picture preceded by a sentence in way of semantic context (Nigam et al., 1992; Willems et al., 2008).

However, since the early studies, evidence has accrued that N400-like negativities can be elicited by multiple experimental manipulations. Kutas and Federmeier (2011) reviewing 30 years of research on the N400 concluded that “semantic anomalies were neither necessary nor sufficient for N400 elicitation.” They proposed that N400 does not index one particular mental operation but “something fundamental about the processing of meaning” suggesting that the meaningful/non-meaningful dimension was more important to elicit this component. Following this line of reasoning, we interpreted the observed amplitude differences in the negative component between the experimental conditions of the present study as an N400-like effect. The inner speech condition was the only clear language-related condition in which participants might

be creating a semantic context. Therefore, the checkerboard stimulus could be integrated as a more disruptive element within the internal discourse than in the other conditions. Obviously, further research and specific experimental manipulations would be necessary to clarify the relationship between this component and the inner speech, something that, to our knowledge, has not been studied so far.

In summary, our results showed that when attention is engaged in a visual imagery task, the reduction in sensory processing of visual stimuli is larger than when attention is engaged in an inner speech. Besides, visual cortical inhibition during visual imagery is larger than during inner speech condition. Finally, the larger amplitude of the N400-like component during inner speech condition reveals the differential nature of this representational format and evidences differences in late processing stages between visual imagery and inner speech.

5. General conclusions

The decoupling hypothesis argues that some mental processes can serve both during self-generated and externally generated thoughts, overlapping some functions. These domain-general processes (for instance, supramodal attentional control processes) are engaged during mind wandering to ensure the integrity and continuity of the internal train of thought, but at the cost of impairing the perceptual processing regardless of sensory modality (Smallwood, 2013a). In the present study, we showed that when attention is engaged in a self-generated thought, there is a decoupling regardless of representational format of thoughts, consistent with the hypothesis that domain-general processes are engaged during these episodes.

Besides, according to the process-occurrence framework proposed by Smallwood (2013a), decoupling would be a process that ensure continuity of internal train of thought once initiated, that is, decoupling would occur regardless of how the internal train of thoughts was triggered (Smallwood, 2013b). Perceptual decoupling has been widely supported by studies of spontaneous mind wandering (Baird et al., 2014; Kam et al., 2011), but now, we also showed that decoupling operates if the occurrence of self-generated thought is controlled as part of a task.

On the other hand, we also showed that in addition to domain-general processes, there are domain-specific processes that could affect the perceptual decoupling. Specifically, we found that if a thought of a given representational format use the same processing resources that incoming sensory information, then the sensory processing of that information will be reduced to a larger extent.

In summary, we showed that perceptual decoupling occurs when there is a controlled shift of attention to a self-generated thought. Furthermore, we showed that some aspects of decoupling depend on domain-general processes which could be related with maintaining inward-turned attention, while other aspects of decoupling are content-

dependent or domain-specific processes. The latter could enhance the decoupling when sensory information and thoughts in a given representational format compete for processing resources (Fig. 5). Finally, the present work advances a method for an objective phenomenological discrimination between auditory and visual mental representations.

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Conflict of interest

The authors declare no competing financial interests.

References

- Andrews-Hanna, J.R., Kaiser, R.H., Turner, A.E., Reineberg, A.E., Godinez, D., Dimidjian, S., Banich, M.T., 2013. A penny for your thoughts: dimensions of self-generated thought content and relationships with individual differences in emotional wellbeing. *Front. Psychol.* 4, 900. <http://dx.doi.org/10.3389/fpsyg.2013.00900>.
- Baird, B., Smallwood, J., Lutz, A., Schooler, J.W., 2014. The decoupled mind: mind-wandering disrupts cortical phase-locking to perceptual events. *J. Cogn. Neurosci.* http://dx.doi.org/10.1162/jocn_a_00656.
- Baird, B., Smallwood, J., Schooler, J.W., 2011. Back to the future: autobiographical planning and the functionality of mind-wandering. *Conscious. Cogn.* 20 (4), 1604–1611. <http://dx.doi.org/10.1016/j.concog.2011.08.007>.
- Barron, E., Riby, L.M., Greer, J., Smallwood, J., 2011. Absorbed in thought: the effect of mind wandering on the processing of relevant and irrelevant events. *Psychol. Sci.* 22 (5), 596–601. <http://dx.doi.org/10.1177/0956797611404083>.
- Braboszcz, C., Delorme, A., 2011. Lost in thoughts: neural markers of low alertness during mind wandering. *NeuroImage* 54 (4), 3040–3047. <http://dx.doi.org/10.1016/j.neuroimage.2010.10.008>.
- Cooper, N.R., Croft, R.J., Dominey, S.J., Burgess, A.P., Gruzeliy, J.H., 2003. Paradox lost? Exploring the role of alpha oscillations during externally vs. internally directed attention and the implications for idling and inhibition hypotheses. *Int. J. Psychophysiol.* 47 (1), 65–74.
- Cosmelli, D., Lopez, V., Lachaux, J.P., Lopez-Calderon, J., Renault, B., Martinerie, J., Aboitiz, F., 2011. Shifting visual attention away from fixation is specifically associated with alpha band activity over ipsilateral parietal regions. *Psychophysiology* 48 (3), 312–322. <http://dx.doi.org/10.1111/j.1469-8986.2010.01066.x>.
- Christoff, K., Gordon, A.M., Smallwood, J., Smith, R., Schooler, J.W., 2009. Experience sampling during fMRI reveals default network and executive system contributions to mind wandering. *Proc. Natl. Acad. Sci. U. S. A.* 106 (21), 8719–8724. <http://dx.doi.org/10.1073/pnas.0900234106>.
- Delorme, A., Makeig, S., 2004. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *J. Neurosci. Methods* 134 (1), 9–21. <http://dx.doi.org/10.1016/j.jneumeth.2003.10.009>.
- Di Russo, F., Martinez, A., Sereno, M.I., Pitzalis, S., Hillyard, S.A., 2002. Cortical sources of the early components of the visual evoked potential. *Hum. Brain Mapp.* 15 (2), 95–111.
- Donchin, E., 1981. Presidential address, 1980. Surprise!... Surprise? *Psychophysiology* 18 (5), 493–513.
- Eimer, M., 2014. The time course of spatial attention: insights from event-related brain potentials. In: Nobre, A.C., Kastner, S. (Eds.), *The Oxford Handbook of Attention*. Oxford University Press.
- Eimer, M., Driver, J., 2000. An event-related brain potential study of cross-modal links in spatial attention between vision and touch. *Psychophysiology* 37 (5), 697–705.
- Eimer, M., Van Velzen, J., 2002. Crossmodal links in spatial attention are mediated by supramodal control processes: evidence from event-related potentials. *Psychophysiology* 39 (4), 437–449. doi: 10.1017/S0048577201393162.
- Farah, M.J., Wong, A.B., Monheit, M.A., Morrow, L.A., 1989. Parietal lobe mechanisms of spatial attention: modality-specific or supramodal? *Neuropsychologia* 27 (4), 461–470.
- Foxe, J.J., Snyder, A.C., 2011. The role of alpha-band brain oscillations as a sensory suppression mechanism during selective attention. *Front. Psychol.* 2, 154. <http://dx.doi.org/10.3389/fpsyg.2011.00154>.
- Gorgolewski, K.J., Lurie, D., Urchs, S., Kipping, J.A., Craddock, R.C., Milham, M.P., ... Smallwood, J., 2014. A correspondence between individual differences in the brain's intrinsic functional architecture and the content and form of self-generated thoughts. *PLoS One* 9 (5), e97176. <http://dx.doi.org/10.1371/journal.pone.0097176>.
- Hanslmayr, S., Gross, J., Klimesch, W., Shapiro, K.L., 2011. The role of alpha oscillations in temporal attention. *Brain Res. Rev.* 67 (1–2), 331–343. <http://dx.doi.org/10.1016/j.brainresrev.2011.04.002>.
- Hillyard, S.A., Anillo-Vento, L., 1998. Event-related brain potentials in the study of visual selective attention. *Proc. Natl. Acad. Sci. U. S. A.* 95 (3), 781–787.

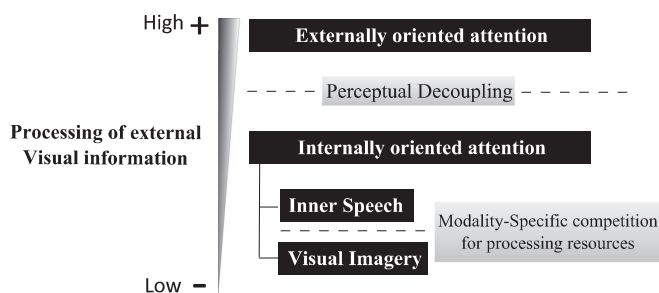


Fig. 5. Schematic representation of visual processing levels during external attention and visual/auditory verbal imagery. Sensory processing to visual stimuli is high when attention is oriented to external visual demands. When a self-generated thought is initiated, attention becomes decoupled from perception, and therefore, there is a reduction in sensory processing of visual information. Furthermore, if a thought is visually represented as a mental image, this impairs the visual sensory response to a larger extent than if the thought do not involve visual representation, such as auditory inner speech.

- Hillyard, S.A., Vogel, E.K., Luck, S.J., 1998. Sensory gain control (amplification) as a mechanism of selective attention: electrophysiological and neuroimaging evidence. *Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci.* 353 (1373), 1257–1270. <http://dx.doi.org/10.1098/rstb.1998.0281>.
- Johnson, J.A., Zatorre, R.J., 2005. Attention to simultaneous unrelated auditory and visual events: behavioral and neural correlates. *Cereb. Cortex* 15 (10), 1609–1620. <http://dx.doi.org/10.1093/cercor/bhi039>.
- Johnson, J.A., Zatorre, R.J., 2006. Neural substrates for dividing and focusing attention between simultaneous auditory and visual events. *NeuroImage* 31 (4), 1673–1681. <http://dx.doi.org/10.1016/j.neuroimage.2006.02.026>.
- Kam, J.W., Dao, E., Blinn, P., Krigolson, O.E., Boyd, L.A., Handy, T.C., 2012. Mind wandering and motor control: off-task thinking disrupts the online adjustment of behavior. *Front. Hum. Neurosci.* 6, 329. <http://dx.doi.org/10.3389/fnhum.2012.00329>.
- Kam, J.W., Dao, E., Farley, J., Fitzpatrick, K., Smallwood, J., Schooler, J.W., Handy, T.C., 2011. Slow fluctuations in attentional control of sensory cortex. *J. Cogn. Neurosci.* 23 (2), 460–470. <http://dx.doi.org/10.1162/jocn.2010.21443>.
- Keil, A., Debener, S., Gratton, G., Junghofer, M., Kappenman, E.S., Luck, S.J., ... Yee, C.M., 2014. Committee report: publication guidelines and recommendations for studies using electroencephalography and magnetoencephalography. *Psychophysiology* 51 (1), 1–21. <http://dx.doi.org/10.1111/psyp.12147>.
- Kelly, S.P., Lalor, E.C., Reilly, R.B., Foxe, J.J., 2006. Increases in alpha oscillatory power reflect an active retinotopic mechanism for distracter suppression during sustained visuospatial attention. *J. Neurophysiol.* 95 (6), 3844–3851. <http://dx.doi.org/10.1152/jn.01234.2005>.
- Killingworth, M.A., Gilbert, D.T., 2010. A wandering mind is an unhappy mind. *Science* 330 (6006), 932. <http://dx.doi.org/10.1126/science.1192439>.
- Klimesch, W., 1999. EEG alpha and theta oscillations reflect cognitive and memory performance: a review and analysis. *Brain Res. Brain Res. Rev.* 29 (2–3), 169–195.
- Kosslyn, S.M., Ganis, G., Thompson, W.L., 2001. Neural foundations of imagery. *Nat. Rev. Neurosci.* 2 (9), 635–642. <http://dx.doi.org/10.1038/35090055>.
- Kutas, M., Federmeier, K.D., 2011. Thirty years and counting: finding meaning in the N400 component of the event-related brain potential (ERP). *Annu. Rev. Psychol.* 62, 621–647. <http://dx.doi.org/10.1146/annurev.psych.093008.131123>.
- Kutas, M., Hillyard, S.A., 1980. Reading senseless sentences: brain potentials reflect semantic incongruity. *Science* 207 (4427), 203–205.
- Luck, S.J., 2005. *An Introduction to the Event-Related Potential Technique*. MIT Press, Cambridge, Mass.
- Luck, S.J., Hillyard, S.A., 1995. The role of attention in feature detection and conjunction discrimination: an electrophysiological analysis. *Int. J. Neurosci.* 80 (1–4), 281–297.
- Mangun, G.R., Hillyard, S.A., 1988. Spatial gradients of visual attention: behavioral and electrophysiological evidence. *Electroencephalogr. Clin. Neurophysiol.* 70 (5), 417–428.
- McGuire, P.K., Silbersweig, D.A., Murray, R.M., David, A.S., Frackowiak, R.S., Frith, C.D., 1996. Functional anatomy of inner speech and auditory verbal imagery. *Psychol. Med.* 26 (1), 29–38.
- Mo, J., Liu, Y., Huang, H., Ding, M., 2013. Coupling between visual alpha oscillations and default mode activity. [research support, N.I.H., extramural]. *NeuroImage* 68, 112–118. <http://dx.doi.org/10.1016/j.neuroimage.2012.11.058>.
- Nigam, A., Hoffman, J.E., Simons, R.F., 1992. N400 to semantically anomalous pictures and words. *J. Cogn. Neurosci.* 4 (1), 15–22. <http://dx.doi.org/10.1162/jocn.1992.4.1.15>.
- Nobre, K., Kastner, S., 2014. *The Oxford Handbook of Attention*. Oxford University Press, Oxford.
- O'Craven, K.M., Kanwisher, N., 2000. Mental imagery of faces and places activates corresponding stimulus-specific brain regions. *J. Cogn. Neurosci.* 12 (6), 1013–1023.
- Payne, L., Guillory, S., Sekuler, R., 2013. Attention-modulated alpha-band oscillations protect against intrusion of irrelevant information. *J. Cogn. Neurosci.* 25 (9), 1463–1476. http://dx.doi.org/10.1162/jocn_a_00395.
- Peirce, J.W., 2007. PsychoPy—psychophysics software in Python. *J. Neurosci. Methods* 162 (1–2), 8–13. <http://dx.doi.org/10.1016/j.jneumeth.2006.11.017>.
- Poerio, G.L., Totterdell, P., Miles, E., 2013. Mind-wandering and negative mood: does one thing really lead to another? *Conscious. Cogn.* 22 (4), 1412–1421. <http://dx.doi.org/10.1016/j.concog.2013.09.012>.
- Polich, J., 2007. Updating P300: an integrative theory of P3a and P3b. *Clin. Neurophysiol.* 118 (10), 2128–2148. <http://dx.doi.org/10.1016/j.clinph.2007.04.019>.
- Posner, M.I., 1980. Orienting of attention. *Q. J. Exp. Psychol.* 32 (1), 3–25.
- Ruby, F.J., Smallwood, J., Engen, H., Singer, T., 2013. How self-generated thought shapes mood—the relation between mind-wandering and mood depends on the socio-temporal content of thoughts. *PLoS One* 8 (10), e77554. <http://dx.doi.org/10.1371/journal.pone.0077554>.
- Schooler, J.W., Smallwood, J., Christoff, K., Handy, T.C., Reichle, E.D., Sayette, M.A., 2011. Meta-awareness, perceptual decoupling and the wandering mind. *Trends Cogn. Sci.* 15 (7), 319–326. <http://dx.doi.org/10.1016/j.tics.2011.05.006>.
- Schroeder, C.E., Herrero, J.L., Haegens, S., 2014. Neuronal dynamics and the mechanistic bases of selective attention. In: Nobre, A.C., Kastner, S. (Eds.), *The Oxford Handbook of Attention*. Oxford University Press.
- Seli, P., Carriere, J.S., Smilek, D., 2014. Not all mind wandering is created equal: dissociating deliberate from spontaneous mind wandering. *Psychol. Res.* <http://dx.doi.org/10.1007/s00426-014-0617-x>.
- Sereno, M.I., Dale, A.M., Reppas, J.B., Kwong, K.K., Belliveau, J.W., Brady, T.J., ... Tootell, R.B., 1995. Borders of multiple visual areas in humans revealed by functional magnetic resonance imaging. *Science* 268 (5212), 889–893.
- Shapiro, K., Hanslmayr, S., 2014. The role of brain oscillations in the temporal limits of attention. In: Nobre, A.C., Kastner, S. (Eds.), *The Oxford Handbook of Attention*. Oxford University Press.
- Shergill, S.S., Bullmore, E.T., Brammer, M.J., Williams, S.C., Murray, R.M., McGuire, P.K., 2001. A functional study of auditory verbal imagery. *Psychol. Med.* 31 (2), 241–253.
- Smallwood, J., 2013a. Distinguishing how from why the mind wanders: a process-occurrence framework for self-generated mental activity. *Psychol. Bull.* 139 (3), 519–535. <http://dx.doi.org/10.1037/a0030010>.
- Smallwood, J., 2013b. Searching for the elements of thought: reply to Franklin, Mrazek, Broadway, and Schooler (2013). *Psychol. Bull.* 139 (3), 542–547. <http://dx.doi.org/10.1037/a0031019>.
- Smallwood, J., Beach, E., Schooler, J.W., Handy, T.C., 2008. Going AWOL in the brain: mind wandering reduces cortical analysis of external events. *J. Cogn. Neurosci.* 20 (3), 458–469. <http://dx.doi.org/10.1162/jocn.2008.20037>.
- Smallwood, J., Schooler, J.W., 2006. The restless mind. *Psychol. Bull.* 132 (6), 946–958. <http://dx.doi.org/10.1037/0033-2909.132.6.946>.
- Smallwood, J., Schooler, J.W., 2015. The science of mind wandering: empirically navigating the stream of consciousness. *Annu. Rev. Psychol.* 66, 487–518. <http://dx.doi.org/10.1146/annurev-psych-010814-015331>.
- Snyder, A.C., Foxe, J.J., 2010. Anticipatory attentional suppression of visual features indexed by oscillatory alpha-band power increases: a high-density electrical mapping study. *J. Neurosci.* 30 (11), 4024–4032. <http://dx.doi.org/10.1523/JNEUROSCI.5684-09.2010>.
- Spence, C., Driver, J., 1996. Audiovisual links in endogenous covert spatial attention. *J. Exp. Psychol. Hum. Percept. Perform.* 22 (4), 1005–1030.
- Spence, C., Nicholls, M.E., Driver, J., 2001. The cost of expecting events in the wrong sensory modality. *Percept. Psychophys.* 63 (2), 330–336.
- Stawarczyk, D., Cassol, H., D'Argembeau, A., 2013. Phenomenology of future-oriented mind-wandering episodes. *Front. Psychol.* 4, 425. <http://dx.doi.org/10.3389/fpsyg.2013.00425>.
- Stawarczyk, D., Majerus, S., Maj, M., Van der Linden, M., D'Argembeau, A., 2011. Mind-wandering: phenomenology and function as assessed with a novel experience sampling method. *Acta Psychol.* 136 (3), 370–381. <http://dx.doi.org/10.1016/j.actpsy.2011.01.002>.
- Tootell, R.B., Hadjikhani, N.K., Mendola, J.D., Marrett, S., Dale, A.M., 1998. From retinotopy to recognition: fMRI in human visual cortex. *Trends Cogn. Sci.* 2 (5), 174–183.
- Tusche, A., Smallwood, J., Bernhardt, B.C., Singer, T., 2014. Classifying the wandering mind: revealing the affective content of thoughts during task-free rest periods. *NeuroImage* <http://dx.doi.org/10.1016/j.neuroimage.2014.03.076>.
- Villena-González, M., López, V., Rodríguez, E., 2016. Differential ERP amplitude and spectral power modulations when attention is engaged on visual or verbal/auditory imagery. [Data in Brief]. *NeuroImage* (submitted for publication).
- Willems, R.M., Ozyurek, A., Hagoort, P., 2008. Seeing and hearing meaning: ERP and fMRI evidence of word versus picture integration into a sentence context. *J. Cogn. Neurosci.* 20 (7), 1235–1249. <http://dx.doi.org/10.1162/jocn.2008.20085>.
- Worden, M.S., Foxe, J.J., Wang, N., Simpson, G.V., 2000. Anticipatory biasing of visuospatial attention indexed by retinotopically specific alpha-band electroencephalography increases over occipital cortex. *J. Neurosci.* 20 (6), RC63.