The role of posterior parietal cortex and medial prefrontal cortex in distraction and mind-wandering

Published Version:
Giacometti Giordani L, C.A. (2023). The role of posterior parietal cortex and medial prefrontal cortex in distraction and mind-wandering. NEUROPSYCHOLOGIA, 188, 1-10 [10.1016/j.neuropsychologia.2023.108639].

Availability:
This version is available at: https://hdl.handle.net/11585/944160 since: 2024-04-08

Published:
DOI: http://doi.org/10.1016/j.neuropsychologia.2023.108639

The role of posterior parietal cortex and medial prefrontal cortex in distraction and mind-wandering

Luca Giacometti Giordani[1], Andrea Crisafulli[1], Giovanni Cantarella[1,2], Alessio Avenanti[1,2], and Elisa Ciaramelli[1,2,*]

1. Centre for studies and research in Cognitive Neuroscience, Cesena, Italy
2. Department of Psychology 'Renzo Canestrari', University of Bologna, Bologna, Italy

Luca Giacometti Giordani

Andrea Crisafulli https://orcid.org/0000-0001-6737-0768

Giovanni Cantarella https://orcid.org/0000-0001-5151-7171

Alessio Avenanti https://orcid.org/0000-0003-1139-9996

Elisa Ciaramelli https://orcid.org/0000-0002-4797-8060

*Correspondence to
Elisa Ciaramelli
Dipartimento di Psicologia 'Renzo Canestrari'
Viale Berti-Pichat 5
40126 Bologna Italy
elisa.ciaramelli@unibo.it

Abstract

Distraction reflects a drift of attention away from the task at hand towards task-irrelevant external or internal information (mind-wandering). The right posterior parietal cortex (PPC) and the medial prefrontal cortex (mPFC) are known to mediate attention to external information and mind-wandering, respectively, but it is not clear whether they support each process selectively or rather they play similar roles in supporting both. In this study, participants performed a visual search task including salient color singleton distractors before and after receiving cathodal (inhibitory) transcranial direct current stimulation (tDCS) to the right PPC, the mPFC, or sham tDCS. Thought probes assessed the intensity and contents of mind-wandering during visual search. The results show that tDCS to the right PPC but not mPFC reduced the attentional capture by the singleton distractor during visual search. tDCS to both mPFC and PPC reduced mind-wandering, but only tDCS to the mPFC specifically reduced future-oriented mind-wandering. These results suggest that the right PPC and mPFC play a different role in directing attention towards task-irrelevant information. The PPC is involved in both external and internal distraction, possibly by mediating the disengagement of attention from the current task and its reorienting to salient information, be this a percept or a mental content (mind-wandering). By contrast, the mPFC uniquely supports mind-wandering, possibly by mediating the endogenous generation of future-oriented thoughts capable to draw attention inward, away from ongoing activities.

Keywords: mind-wandering, attention, posterior parietal cortex, medial prefrontal cortex, transcranial direct current stimulation

1. Introduction

Distraction, a common experience of human mental life, reflects a drift of attention away from an ongoing task and towards task-irrelevant yet salient information. There are multiple sources of distraction. Attention can be diverted from its original focus by stimuli in the sensorial world, such as a sudden sound of church bells ringing, the voice of a friend calling, a headache. Our mind, however, can also wander off-task to focus on our inner world, a phenomenon known as mind-wandering (Antrobus et al., 1966; Smallwood & Schooler, 2015; Christoff et al., 2016; Fox et al., 2015; Stawarczyk et al., 2011). The most paradigmatic form of mind-wandering is both stimulus-independent (internally generated) and task-unrelated (Stawarczyk et al., 2011). An example is fantasizing about attending an upcoming concert while swimming.

The neural bases of attention to the external world have long been investigated, while those of mind-wandering have been addressed only more recently, in the last decade (see, for reviews, Christoff et al., 2016; Seli et al., 2018). For the most, these two lines of research have run parallel. This is surprising considering that internal and external sources of information compete for attention, and that our mental life consists in fact of a blend of mental states that are in part goal-directed, and in part reflecting the straying of attention towards internal or external task-irrelevant stimuli. What are the neural bases of our ability to direct attention to internal and external information?

It has long been known that when attention is allocated to the external environment, two different brain networks are engaged, in which the posterior parietal cortex (PPC) figures prominently (Theeuwes, 1991; Corbetta & Shulman, 2002). The dorsal PPC is engaged during the voluntary orienting of attention towards relevant stimuli, whereas the ventral PPC responds to the reorienting of attention towards relevant yet unexpected stimuli (Corbetta et al., 2008). For example, enhanced responses in the ventral PPC, especially in the right hemisphere, are observed when subjects are cued to expect a target at one location but it unexpectedly appears at another (Posner, 1980; Corbetta et al., 2000; Indovina & Macaluso, 2007), or when individuals monitor the environment for infrequent targets (oddballs; e.g., Bledowski et al., 2004; Downar et al., 2000; Stevens et al., 2005). The capture of attention by salient external stimuli may interfere with performance. In a functional neuroimaging (fMRI) study, de Fockert et al. (2004) had participants search for a circle among diamonds (see also Theeuwes, 1991). In 25% of trials, the target (circle) or a distractor (diamond) was a color singleton. The presence of a color singleton distractor interfered with search performance, leading to an increase in reaction times (RTs) to the target (Jonides & Yantis, 1988; Theeuwes, 1991), which was accompanied by activity in the dorsal PPC bilaterally. The role of right PPC in mediating the capture of attention by a perceptually salient distractor singleton is corroborated by causal evidence. Hodsoll, Mevorach and Humphreys (2009) had participants undergo a similar visual search task following the inhibition of the right or left PPC through transcranial magnetic stimulation (TMS). TMS of the right – but not left – PPC reduced the RT cost associated with singleton distractor trials, supporting the view that the right PPC plays a crucial role in mediating shifts of attention towards (distraction from) external sources of information (Mevorach et al., 2006). As well, in a target discrimination task (Heinen et al., 2011), TMS over the right angular gyrus of PPC interfered with bottom-up reorienting of attention. Moreover, patients with lesions to the right PPC may show neglect, a deficit in detecting contralesional stimuli, especially if invalidly cued (Friedrich et al., 1998).

Attention can be captured by internal information as well. Germane to this is the ubiquitous experience of mind-wandering, whereby attention is diverted away from the external environment and current goals towards task-unrelated and stimulus-independent thoughts, such as memories, future plans, and current concerns (Christoff et al., 2016; Stawarczyk, et al., 2011). Like external distraction, mind-wandering is not costless: it interferes with processing of external events (Barron et al., 2011) and performance in the task at hand (Smallwood et al., 2007; Mcvay & Kane, 2010; Franklin et al., 2011). fMRI evidence indicates that mind-wandering is associated with activity in the 'default network', a set of interconnected brain regions that includes the medial prefrontal cortex (mPFC), the medial temporal lobe (MTL), the posterior cingulate cortex, and the lateral temporal and parietal cortex, whose activity is enhanced during relatively passive (as compared with goal-directed) and internally focused states (Mason et al., 2007; Buckner et al., 2008; Christoff et al., 2009). The default network is more engaged during mind-wandering (stimulus-independent and task-unrelated thought) compared to other types of off-task thoughts that are less removed from the current experience, such as external distractions (which are triggered by an external stimulus; e.g., 'was that a thunder?') and task-related thoughts (which are related to the ongoing activity; e.g., 'this task is boring'), though different subregions of the default network respond preferentially to different forms of off-task experience (Stawarczyk et al., 2011). In particular, the mPFC, in both its ventral (vmPFC) and dorsal aspects, seems to be crucially implicated in mind-wandering (Andrews-Hanna et al., 2010). Bernhardt et al. (2014) found that the thickness of mPFC regions is positively related to individuals' tendency to mind-wander (Bernhardt et al., 2014). Further, patients with lesion to the vmPFC show a reduced frequency of mind-wandering compared to healthy and brain-damaged controls. Moreover, their off-task thoughts are mostly present-oriented, and never about the future (Bertossi & Ciaramelli, 2016).

Although previous studies have associated the right PPC and the mPFC with the ability to direct attention to external and internal information, respectively, no study has tested empirically whether these regions support each process selectively, or rather they support both processes (Stawarczyk et al., 2014). Mind-wandering shares cognitive components with external distraction, in that in both cases a task-irrelevant stimulus, be it internal (during mind-wandering) or external, diverts attention from its original focus (Unsworth & McMillan, 2014). According to recent models of attention, the PPC mediates the re-orienting of attention to internal (e.g., memory) in addition to external sources of information (Wagner et al., 2005; Ciaramelli et al., 2008; Cabeza et al., 2008; Ciaramelli & Moscovitch, 2020). The right PPC may act as a convergence node regulating the interaction between the ventral attention network, implicated in detecting salient information (Corbetta et al., 2008; Ciaramelli et al., 2008), and the default network, implicated in generating thought contents (Christoff et al., 2016; Stawarczyk et al., 2011; Ciaramelli & Treves, 2019), allowing the flexible switching of attention between external and internal stimuli, possibly via interactions with the the locus coeruleus-norepinephrine system (Mittner et al., 2016). On this view, the right PPC should be related to mind-wandering, in addition to external attention. On the other hand, there is evidence that mPFC may also support attention towards the external environment under some conditions. Gilbert et al. (2006), for example, found that activity in BA 10 of mPFC was associated with shorter reaction times to external stimuli (see also Gilbert et al., 2005), and lesions to the mPFC can result in poor performance in simple RT tasks (Stuss et al., 2002; Stuss et al., 2005). Whether or not mPFC is causally and uniquely implicated in mind-wandering, therefore, awaits empirical confirmation.

Here we investigate the causal involvement of the right PPC and mPFC in directing attention towards task-irrelevant external and internal information using a task that allows the concomitant assessment of both. In a task modified by Hodsoll et al. (2009), participants searched target circles among distracting diamonds, while the presence of color singleton distractors enabled the assessment of attentional capture by salient external information. The visual search task was occasionally interrupted by thought probes assessing the frequency and contents of off-task thoughts. The effect of singleton distractors on visual search performance served as an index of external attention, whereas the tendency towards mind-wandering served as an index of internal attention. The task was executed both before and after cathodal (inhibitory) tDCS of the right PCC, mPFC, or sham tDCS (see Figure 1).

If the right PPC is primarily implicated in directing attention to the external environment (Corbetta & Shulman, 2002), then cathodal tDCS of the right PPC should reduce the detrimental effect of singleton distractors on visual search (as in Hodsoll et al., 2008), but not mind-wandering. The few studies of mind-wandering following tDCS of right PPC appear consistent with this prediction, though they do not speak to our question directly. Kajimura and Nomura (2015, 2016) have repeatedly shown that applying anodal (excitatory) tDCS to right PPC and concomitant cathodal (inhibitory) tDCS to the lateral prefrontal cortex decreases mind-wandering, indicating that, if anything, the PPC contributes to down-regulating mind-wandering (see also Hasenkamp et al., 2012; Filmer et al., 2021). It is not clear, however, whether the same results would be obtained targeting right PPC alone, or inhibiting (as opposed to enhancing) activity in PPC, as we plan to do. Indeed, in a recent study targeting right PPC with anodal tDCS, Kajimura et al. (2019) found a reduction of mind-wandering, but Coulborn et al. (2020) found no effect. A limit of previous studies is that mind-wandering was not distinguished by externally-triggered forms of off-task thought, such as external distractions and task-related thoughts (Stawarczyk et al., 2011), which may have complicated the detection of a link between the right PPC and internal distraction. Indeed, if the right PPC mediates shifts of attention to the external environment (Corbetta & Shulman, 2002), tDCS-induced inhibition of PPC might have an impact on off-task thoughts triggered by external stimuli, even though it is not expected to reduce mind-wandering. On the other hand, if PPC is implicated in directing attention to both external and internal information (Cabeza et al., 2008; Ciaramelli & Moscovitch, 2020), then tDCS of the PPC should reduce both the distractor effect on visual search and mind-wandering.

Considering that mPFC is a crucial node of the brain default network (Mason et al., 2007; Buckner et al., 2008; Christoff et al., 2009; Stawarczyk, et al., 2011), we predict that cathodal tDCS to mPFC would reduce mind-wandering, but not the capture of attention by external (distractors) stimuli in the visual search task. These predictions are supported by previous evidence that patients with lesion to the ventral mPFC have reduced mind-wandering (Bertossi & Ciaramelli, 2016), but are, if anything, even more distractable than healthy controls by task-irrelevant external information, for example during flanker or Stroop tasks (di Pellegrino et al., 2007, Ziaei et al., 2018).

A final question pertains to the temporality of mind-wandering. Bertossi and Ciaramelli (2016) found a selective reduction of future-oriented mind-wandering in vmPFC patients, consistent with the role of vmPFC in future thinking and future-oriented cognition (Ciaramelli et al., 2021a,b; Schacter et al., 2012; Stawarczyk & D’Argembeau, 2015). However, a tDCS study by the same group did not show a selective role of mPFC in future-oriented mind-wandering (Bertossi et al., 2017), possibly because in that study mind-wandering was not distinguished by external distractions and task-related thoughts, which are typically present-oriented. Therefore, here we re-examine the temporality of mind-wandering, with the prediction that cathodal tDCS to mPFC (but not PPC) would reduce future- more than past-oriented mind-wandering.

2. Materials and Methods

2.1 Participants

Sixty-one right-handed young adults with no self-reported history of neurological or psychiatric disease were recruited from among the students of an introductory psychology course at the University of Bologna for course credits. Participants were randomly allocated to one of three stimulation groups: the PPC group (N = 22, 8 males, to receive cathodal tDCS over the right PPC, see below; mean age = 21.82, SD = 1.59), the mPFC group (N = 21, 8 males, to receive cathodal tDCS over mPFC, see below; mean age = 23.19, SD = 2.44), and the sham group (N = 22, 8 males, to receive sham tDCS, see below; mean age = 22.41, SD = 2.04) (see Table 1). Age ($F = 2.42$, $p = 0.10$) and gender ($\chi^2 = 0.02$, $p = 0.99$) did not differ across stimulation groups. The sample size was determined based on previous studies using tDCS (Axelrod et al. 2015; Bertossi et al., 2017; Kajimura & Nomura, 2015; Kajimura et al., 2019). Participant groups were matched for working memory performance ($p > 0.27$, $\eta^2 < 0.041$ both for accuracy and RTs) and baseline propensity to mind-wander at the Mind Wandering questionnaire (MWQ; $p = 0.36$; $\eta^2 = 0.03$) (Table 1; see Supplementary Materials for more detail on the task/questionnaire). Participants were blind to the type of stimulation they were going to receive, and reported similar (low) levels of discomfort following (PPC, mPFC, or sham) tDCS ($p = 0.2$; $\eta_p^2 = 0.05$). Participants gave informed consent to participate to the study, which was approved by the Bioethical Committee of the University of Bologna and carried out in agreement with international norms (Declaration of Helsinki 1964).

Table 1. Mean values (and SD) for age, working memory accuracy, mind wandering questionnaire (MWQ) scores, and rating of discomfort following tDCS by participant group. PPC = posterior parietal cortex; mPFC = medial prefrontal cortex.

	Age	Working memory	MWQ	Discomfort from tDCS
Sham group	22.41 (2.04)	0.71 (0.18)	16.41 (4.35)	2.00 (1.63)
PPC group	21.82 (1.59)	0.64 (0.21)	16.45 (3.02)	2.64 (2.24)
mPFC group	23.19 (2.44)	0.72 (0.21)	17.90 (4.02)	2.95 (1.24)

2.2 Procedure

2.2.1 tDCS

tDCS was delivered using a battery-driven Eldith constant direct current stimulator (neuroConnGmbH, Ilmenau, Germany). A pair of surface sponge electrodes was soaked in a standard saline solution (NaCl 0.9%) and held in place with elastic rubber bands. In all participants, a monopolar tDCS montage was used, with the cathodal (5x5 cm) and anodal (5x7 cm) electrodes placed over a scalp region and the right deltoid, respectively. We targeted PPC and mPFC using an extracephalic montage, delivering anodal current over the right deltoid, to avoid the confounding effect of a cephalic reference electrode (see also Monti et al. 2007; Im et al. 2012; Bertossi et al. 2017; Avenanti et al. 2018). Participants were randomly assigned to receive either active cathodal stimulation over the right PPC (PPC group), active cathodal stimulation over the mPFC (mPFC group), or sham stimulation (sham group) (see Figure 1). Active tDCS was delivered with a constant current of 2 mA (current density ~0.08 mA/cm2), complying with current safety guidelines (Nitsche et al., 2003). Active stimulation lasted for 15 min, plus 15 sec of ramp-up and ramp-down at the beginning and end of the stimulation. Impedance was constantly controlled and kept below 8 kOhm, with the addition of saline solution whenever needed. There is evidence that this stimulation protocol can affect cortical excitability for up to 30 min after the end of the stimulation, thus covering the entire duration of the visual search test (Nitsche et al., 2008).

In the PPC group, the electrode was positioned in a site corresponding to P4 (right parietal) point of the international 10-20 electroencephalography coordinate system, as in Hodsoll et al. (2008), which corresponds to the right angular gyrus (Mevorach et al., 2006). In the mPFC group, the electrode was positioned over right BA10, one of the clusters most consistently activated during mind-wandering in a recent meta-analysis by Fox et al. (2015). The Montreal Neurological Institute (MNI) peak coordinates for that cluster (x = 3, y = 61, z = 13) were transformed into 10-20 electroencephalography system coordinates using the Münster T2T-converter software (www.neuro03.uni-muenster.de/ger/t2tconv/), and the cathode was applied 1.5 cm to the right of Fpz. In the sham group, the electrodes were placed in the same positions as in the PPC group (in half of the participants) or the mPFC group (in the other half), but the stimulator was turned off after 30 seconds of cathodal stimulation. Thus, participants felt the initial itching sensation associated with active tDCS, but they received no current for the rest of the "stimulation" period. This procedure ensures successful blinding of participants. Immediately after the stimulation, participants rated on a 10-point Likert scale the discomfort they experienced during the stimulation, if any (from 1 – 'no discomfort' to 10 – 'extreme discomfort').

2.2.2 Visual search task and assessment of external distraction

Participants then underwent two sessions of a visual search task (lasting about 15 minutes each), one before and one after the tDCS stimulation, with occasional thought probes aimed at assessing mind-wandering (see Figure 1). The ongoing task was a visual search task modified from Hodsoll et al. (2008) to include thought probes (see below). Participants sat at 70 cm from the computer monitor. The visual search display consisted of 6 shapes positioned on a circle of radius 4.6° from the fixation cross. One of the 6 shapes was a circle of diameter 1.9° (target), and the remaining 5 shapes were diamonds of 1.7° square, meaning that the circle and the diamonds occupied approximately the same area. In the centre of each of the six shapes was a segment of length 1° that could be oriented vertically (in 3 cases) or horizontally (in the other 3 cases). The vertical and horizontal orientations were randomized across the 6 segments/shapes.

A trial consisted of a fixation cross for 500 ms, followed by the search displays that were present until a response was made. Participants had to signal whether the orientation of a line within the target circle was horizontal or vertical, by pressing the left-arrow key or the up-arrow key, respectively (Figure 1). A session of the visual search task consisted of 350 trials. In 210 of the 350 trials, all shapes and segments were gray (Standard condition), whereas the remainder contained a green color singleton shape, which could be the target circle (70 trials; Singleton target condition), or a diamond distractor (70 trials; Singleton distractor condition). The effect of color singletons on visual search was assessed by comparing visual search performance in the Singleton distractor or Singleton target conditions with that in the Standard condition with no color singleton shape. Performance costs associated with the Singleton distractor (vs. Standard) condition were used as an index of attention towards task-irrelevant *external* information.

2.2.2.1 Assessment of mind-wandering

Mind-wandering was assessed through 10-12 'thought probes' presented during each session (pre-tDCS, post-tDCS) of the visual search task, at a rate of approximately one thought probe every 25-35 visual search trials. Thought probes were presented visually, as a series of three screens. First, participants were required to rate, on a Visual Analog Scale (VAS), the degree to which immediately before the probe their attention was on-task (focused on performing the task) vs. off-task (focused on something unrelated to doing the task), from 0 – ‘completely on-task’ to 100 – ‘completely off-task’. In a second screen, participants then classified the thoughts they were having just before they were interrupted into 4 qualitative categories: (1) on-task thoughts (i.e., thoughts related to doing the visual search task; e.g., "the segment is horizontal so I press this key"), (2) internal thoughts (**mind-wandering**; i.e., thoughts unrelated to the task and originated endogenously; e.g., "I am so going for a walk after this!"), (3) task-related thoughts (i.e., thoughts triggered by the task, but not necessarily functional to doing the task; e.g., "this task is so boring"), and (4) external distractions (i.e., thoughts triggered by external stimuli; e.g., "Was that a thunder?"). If participants chose category 2, a third screen further probed them to specify whether the internal thought they were having focused on (1) the past (e.g., “The holiday in Turin was the worst ever”), (2) the present (e.g., “I wonder what my girlfriend is doing now”), (3) the future (e.g., “I am seeing the dentist later”), (4) atemporal, 'semantic' considerations (e.g. “I’m lucky to have a friend like her”), or (5) whether they were unaware about the temporal connotation of their thoughts . Internal thoughts, which are both stimulus-independent and task-unrelated (Stawarczyk et al., 2011), were used as an index of attention towards task-irrelevant *internal* information.

Participants were familiarized with the task with a short pilot session comprising 25 to 35 visual search trials and 1 mind-wandering assessment at the end. The software MATLAB R2015a (MathWorks, Inc., Natick, MA) with Psychtoolbox (Brainard, 1997) was used to run the visual search task and record accuracy and response times (RTs) as well as mind-wandering ratings.

Insert Figure 1 about here

3. Results

3.1 Effect of tDCS on visual search

Trials with response times (RTs) more/less than three standard deviations from each participant’s mean (1.5% of RTs) were excluded from the analysis. RTs were longer in the Singleton distractor compared to the Singleton target and Standard (singleton absent) conditions (see Table 2). Accuracy was very high across conditions, with minimal changes again in the direction of lower performance in the Singleton distractor compared to the other conditions (See Table 3).

Table 2. Mean RTs (and SD) for correct responses by participant group, visual search condition, and session. PPC = posterior parietal cortex; mPFC = medial prefrontal cortex.

	No Singleton		**Singleton Target**		**Singleton Distractor**	
	pre-tDCS	*post-tDCS*	*pre-tDCS*	*post-tDCS*	*pre-tDCS*	*post-tDCS*
Sham group	613 (75)	577 (69)	582 (75)	548 (74)	725 (112)	679 (102)
PPC group	621 (50)	576 (40)	597 (46)	550 (37)	707 (79)	631 (54)
mPFC group	609 (60)	567 (49)	589 (63)	544 (47)	698 (96)	639 (76)

Table 3. Mean accuracy (and SD) in the visual search task by participant group, visual search condition, and session. PPC = posterior parietal cortex; mPFC = medial prefrontal cortex.

	No Singleton		**Singleton Target**		**Singleton Distractor**	
	pre-tDCS	*post-tDCS*	*pre-tDCS*	*post-tDCS*	*pre-tDCS*	*post-tDCS*
Sham group	0.99 (0.01)	0.98 (0.01)	0.99 (0.02)	0.99 (0.02)	0.98 (0.02)	0.99 (0.02)
PPC group	0.98 (0.02)	0.98 (0.02)	0.98 (0.02)	0.98 (0.02)	0.97 (0.03)	0.98 (0.02)
mPFC group	0.98 (0.02)	0.98 (0.02)	0.99 (0.01)	0.98 (0.02)	0.98 (0.02)	0.97 (0.03)

For data analysis, RTs and accuracy relative to each singleton condition were combined in an ‘inverse efficacy score’, computed as iRTs = RTs/accuracy (Townsend & Ashby, 1978; 1983; see also Kajimura et al., 2019), which accounts for changes in both RTs and accuracy data, therefore controlling for potential speed/accuracy trade-offs (see Table 4).

Table 4. Mean inverse efficacy scores (iRTs) (and SD), measured as the ratio between RTs and accuracy, by participant group, visual search condition, and session. PPC = posterior parietal cortex; mPFC = medial prefrontal cortex.

	No Singleton		**Singleton Target**		**Singleton Distractor**	
	pre-tDCS	*post-tDCS*	*pre-tDCS*	*post-tDCS*	*pre-tDCS*	*post-tDCS*
Sham group	620 (75)	588 (68)	589 (75)	555 (75)	739 (116)	688 (98)
PPC group	631 (50)	590 (42)	610 (44)	560 (39)	728 (81)	645 (57)
mPFC group	620 (56)	577 (46)	593 (61)	554 (47)	711 (99)	659 (77)

In a preliminary analysis, we made sure that participant groups were matched with respect to their baseline performance in the visual search task (pre-tDCS session), and that we could replicate the previously described effect of a singleton distractor on visual search (Theeuwes, 1991; De Fockert et al., 2004; Hodsoll et al., 2009) despite we had thought probes for the assessment of mind-wandering embedded in the visual search task. An ANOVA on iRTs (i.e., =RTs/Accuracy) with Stimulation group (PPC, mPFC, sham) and Singleton condition (singleton distractor, singleton target, standard) as factors yielded a main effect of Singleton condition ($F_{2,124} = 231.03$; $p = 0.0001$; $\eta_p^2 = 0.78$). Post hoc comparisons, run with the Scheffè test, showed that iRTs in the Singleton distractor condition (M = 726 ms) were significantly longer than those in the Standard condition (M = 624 ms; p = 0.0001), which in turn were longer than those in the Singleton target condition (M = 597 ms; p = 0.0001). There was no effect of Stimulation group or Singleton condition x Stimulation group interaction ($F \leq 1.72$; $p \geq 0.19$; $\eta_p^2 \leq 0.05$ in all cases). This analysis confirms that the presence of a singleton distractor interfered with visual search performance, and that participant groups had comparable baseline visual search abilities (see Table 4).

To investigate the effect of tDCS on external attention, we computed a 'distractor effect index' subtracting the iRTs to the circle target in the absence of distractors (Standard condition) from those attained in the presence of the singleton distractor (Distractor effect = $iRTs_{Singleton\ distractor}$ –

$iRTs_{Standard}$), separately for the pre- and post-tDCS sessions (see Figure 2). The distractor effect was then subject to an ANOVA with Stimulation group (PPC, mPFC, sham) and Session (pre-tDCS, post-tDCS) as factors. There was a significant Stimulation group x Session interaction ($F_{2,62} = 3.88$; p = 0.03; $\eta_p^2 = 0.11$). Scheffè post-hoc tests showed that in the pre-tDCS session the distractor effect was comparable across Stimulation groups (p > 0.83 in all cases). As predicted, cathodal tDCS over PPC attenuated the distractor effect significantly (p = 0.001), whereas no change in the distractor effect was observed from the pre- to the post-tDCS sessions in participants who received sham or mPFC tDCS (both ps > 0.51). The same ANOVA on the effect of a singleton target on visual search (Target effect = $iRTs_{Standard} - iRTs_{Singleton\ target}$) evinced instead no significant effects ($F \leq 2.30$; $p > 0.15$; $\eta_p^2 \leq 0.10$ in all cases; see Figure 3).

Insert Figure 2 and Figure 3 about here

3.2 Effect of tDCS on Mind Wandering

Mind-wandering score. First, we calculated an off-task thought score considering both the frequency of off-task thoughts and their intensity (as assessed with the VAS) by multiplying these variables (we obtain the same findings in all the analyses also if we analyze only the frequency of off-task events, regardless of their intensity), separately for each type of off-task thought and temporal focus (see Table 5).

In a preliminary analysis, we made sure that participant groups exhibited a similar propension towards different types of off-task thought at baseline (pre-tDCS session; Table 5). The variables were in most cases non-normally distributed (as indicated by visual inspection and the Shapiro-Wilk test), and therefore the analyses were run with non-parametric tests. We conducted Kruskal-Wallis ANOVAs on the off-task thought score for internal thoughts (mind-wandering), external distractions, and task-related thoughts, separately, and for the different temporal (past, present, future) subcategories of internal thoughts, with Stimulation group as factor. No significant group differences emerged ($H < 3.27$; ps > 0.20 in all cases; Table 5).

Table 5. Mean off-task thought scores (and SD) by type of off-task thought, participant group, visual search condition. PPC = posterior parietal cortex; mPFC = medial prefrontal cortex.

	Internal thoughts (mind-wandering)		**External distractions**		**Task-related thoughts**	
	pre-tDCS	*post-tDCS*	*pre-tDCS*	*post-tDCS*	*pre-tDCS*	*post-tDCS*
Sham group	229 (161)	388 (167)	73 (48)	36 (46)	101 (101)	83 (72)
PPC group	267 (185)	334 (259)	79 (90)	74 (78)	94 (77)	98 (86)
mPFC group	301 (222)	369 (216)	98 (65)	69 (59)	108 (89)	74 (60)

We first described off-task score changes between sessions in each group, by comparing the score relative to different types of off-task-thought (Table 5) from the pre-tDCS to the post-tDCS session within each participant group, using the Wilcoxon signed rank tests. Internal thoughts generally increased from the first (pre-tDCS) to the second (post-tDCS) session. This increase in internal thoughts was significant in the sham group ($W = 9.00$; $p = 0.001$), significant but less pronounced in the mPFC group ($W = 55.00$; $p = 0.04$), and present only as a non-significant trend in the PPC group ($p = 0.09$). External distractions decreased significantly across sessions in the sham group ($W = 189.00$; $p = 0.01$) but did not change in the PPC ($p = 0.73$) and mPFC group ($p = 0.08$). Task-related thoughts decreased significantly from the pre- to the post-tDCS session in the mPFC group ($W = 149.00$; $p = 0.03$) but did not change significantly in the PPC ($p = 0.94$) and sham groups ($p = 0.48$). This initial set of analyses show that the passage of time generally resulted in changes in mind-wandering, with internal thoughts that tended to increase with time, and externally-driven forms of thought (external distractions and task-related thoughts) that tended to decrease with time, albeit to a variable degree across groups (Table 5).

We then investigated directly whether tDCS altered the magnitude of these changes. We computed change indices for internal thoughts, external distractions, and task-related thoughts as the difference in off-task scores between the post-tDCS and the pre-tDCS session for each category of off-task thought separately (see Figure 4). We conducted Kruskal-Wallis ANOVAs on each of these change indices with Stimulation group as factor. The ANOVA on the change index for internal thoughts yielded a significant effect of Stimulation group ($H = 7.84$; $p = 0.02$). Post hoc comparisons, performed with the Dunn test, showed that, compared to sham stimulation, cathodal tDCS to both the PPC ($p = 0.01$) and mPFC ($p = 0.04$) attenuated the increase in internal thoughts observed in the post- vs. pre-tDCS session significantly, with no difference between PPC and mPFC stimulation ($p = 0.27$). By contrast, the Kruskal-Wallis ANOVAs on change indices for external distractions and task-related thoughts gave no significant results ($H < 1.55$, $p > 0.54$ in both cases). This second set of analyses showed that inhibition of both mPFC and PPC reduced the normal tendency of internal thoughts to increase across sessions, indicating that both regions are crucially linked to mind-wandering.

Insert Figure 4 about here

3.2.1 Temporality of mind-wandering

A final observation concerns the temporality of internal thoughts (Supplementary Table 1). The increase in internal thoughts in the Sham group from the pre-tDCS to the post-tDCS session was driven by future-oriented thoughts, which increased significantly across sessions ($W = 9.00$; $p < 0.001$). The increase in future-oriented internal thoughts was also observed in the PPC group ($W = 47.00$; $p = 0.03$), but not significantly in the mPFC group ($p = 0.16$). Internal thoughts with a different temporal focus (past, present, atemporal) did not change significantly between sessions across groups ($W < 93.00$, $p > 0.07$ in all cases). Given that mPFC and the right PPC have been associated respectively with future-oriented (Ciaramelli et al., 2021) and past-oriented self-projection (Anelli et al., 2019), we also analyzed a ‘future thought index’, calculated as the difference between future-oriented and past-oriented internal thoughts, separately for the pre- and post-tDCS session. We then subtracted the future thought index at the pre-tDCS session from that at the post-tDCS session and compared this difference score across participant groups (see Figure 5). Mann–Whitney tests showed that, compared to sham tDCS, cathodal tDCS of mPFC (W = 315.00; p = 0.04), but not PPC (W = 190.00 ; p = 0.23), reduced the increase in the future thought index observed between sessions, attenuating the tendency of internal thoughts to become more future-oriented from the first (pre-tDCS) to the second (post-tDCS) session, in line with previous reports of reduced future-oriented mind-wandering following mPFC lesions (Bertossi & Ciaramelli, 2016).

Insert Figure 5 about here

4. Discussion

The present study assessed the neural bases of the attentional capture by external and internal information by interfering with the activity of the right PPC and mPFC during a visual search task that allowed the concomitant evaluation of the two types of distraction.

First, we replicated previous findings (Mevorach et al., 2006; Hodsoll et al., 2009) that the presence of a color singleton distractor caused significant visual search costs, despite the insertion of thought probes that modified the original structure of the task (Hodsoll et al., 2008). These findings are consistent with a capture of attention by the colored distractor, which interferes with target detection. Notably, the detrimental effect of the distractor on visual search was reduced following cathodal tDCS of the right PPC. In the PPC stimulation group, indeed, distractor-induced performance costs decreased significantly from the pre- to the post-tDCS session, as if the distractor were less capable to capture attention bottom-up. The same decrement of distractor-induced performance costs was not present in participants receiving mPFC or sham tDCS. These findings reinforce the view that right PPC is implicated in mediating automatic shifts of attention to task-irrelevant external information. By contrast, our findings argue against a role for mPFC in external distraction.

Next, we found that individuals mind-wandered intensely during visual search, which mainly involved generating endogenously thoughts unrelated to the task (internal thoughts; see Bertossi et al., 2017: Killingsworth & Gilbert, 2010; Smallwood & Schooler, 2015). Mind-wandering interfered with the ongoing task (see also Smallwood et al., 2007; Mcvay and Kane, 2010; Franklin et al., 2011): a supplementary analysis showed that individuals indeed were faster and less accurate in trials preceding intense vs. weak mind-wandering reports, which is indicative of more impulsive responding (see Supplementary Material). Across participant groups, internal thoughts tended to increase from the pre- to the post-tDCS sessions (see also Bertossi et al., 2017). This is presumably because, with time, participants generally became more efficient in the task, or bored, and dedicated more resources to mind-wandering (Smallwood et al., 2003; Mittner et al., 2016). Crucially, this increase of mind-wandering was attenuated by cathodal tDCS, whether it was delivered to mPFC, as predicted, or even to PPC, suggesting that both regions are associated with the generation of mind-wandering.

As a core region of the default network (Stawarkcyz et al., 2011), the mPFC is an important neural substrate of mind-wandering (Andrews-Hanna et al., 2010, Christoff et al., 2009; Fox et al., 2015). This evidence is corroborated by lesion studies showing reduced (future-oriented) mind-wandering in vmPFC patients (Bertossi & Ciaramelli, 2016; see also Bernhardt et al., 2014; O'Callaghan et al., 2019; Philippi et al. 2021). vmPFC patients are also impaired in the voluntary construction of complex events, with a more prominent impairment of future event construction (Bertossi et al., 2016a,b; McCormick et al., 2018). For example, Bertossi et al. (2016a), found a reduced experiential index while constructing future compared to atemporal scenarios in vmPFC patients but not in control patients and healthy controls (Bertossi et al., 2016a). Ciaramelli et al. (2021a) showed a selective impairment in self-projection towards a future (compared to past or present) time perspective and in the recognition of future (compared to past) events in vmPFC patients compared to healthy and brain-damaged controls, highlighting the role of vmPFC in future-oriented cognition (Stawarczyk & D'Argembeau, 2015). It is possible, therefore, that vmPFC contributes to the construction of the (future-oriented) mental contents that typically populate mind-wandering, possibly by mediating schema-related knowledge driving event construction (Moscovitch et al., 2016; Ciaramelli et al., 2019; Ciaramelli & Treves, 2019; D'Argembeau, 2020). On this view, the tDCS-induced inhibition of mPFC downregulated mind-wandering by reducing the quality of constructed (future) events, rendering them less capable to draw attention inward. Consistent with this hypothesis is the present evidence that cathodal tDCS over mPFC reduced future-oriented mind-wandering relatively more than past-oriented mind-wandering (as in Bertossi & Ciaramelli, 2016), which aligns with the asymmetry in future vs. past event construction observed in vmPFC patients (Bertossi et al., 2016; see also Ciaramelli et al., 2021a). An alternative view is that mPFC mediates the meta-awareness associated with mind-wandering, that is, the explicit knowledge about the current contents of thought (Schooler et al., 2011). On this view, inhibition of mPFC would reduce the frequency with which people become aware of, hence report, mind-wandering (Smallwood & Schooler, 2015). Were this the case, however, cathodal tDCS of vmPFC should cause a general underreporting of off-task experiences, including task reflections and external distractions, while we observed a selective reduction of internal thoughts.

Our results show that also cathodal tDCS of the right PPC reduced mind-wandering compared to sham stimulation, suggesting that the right PPC is necessary to direct attention towards internal, in addition to external, information. This findings aligns with recent models of attention that maintain that the right PPC mediates the flexible allocation of attentional resources between external and internal information depending on the relative salience of percepts and mental contents (i.e., memories, personal goals, current concerns), modulating the activity and functional connectivity with the ventral attention network and the default network (Mittner et al., 2016; Corbetta et al., 2008; Cabeza et al., 2012; Christoff et al., 2016; Kajimura et al., 2019; Ciaramelli & Moscovitch, 2020). Of course, one could argue that because both types of active tDCS led to a reduction in mind-wandering, inhibiting any other brain region would do as well. We do not think this is likely. First, in a previous tDCS study, inhibiting the occipital cortex did not affect mind-wandering (Bertossi et al., 2017). Moreover, the present study evinced some evidence of regional specificity, with the inhibition of mPFC, but not PPC, attenuating future-oriented more than past-oriented mind-wandering. This finding is compatible with the idea that during mind-wandering the right PPC mediates attention to salient internal information (regardless of its temporal focus; see also Berryhill et al., 2007; Ciaramelli et al., 2010), whereas mPFC mediates the construction of future-oriented mental contents capable to capture attention. An interesting question for future research pertains to the differential roles of the right and left PPC in mind-wandering. Previous evidence suggests a more prominent role of the right PPC in directing attention to external stimuli (Corbetta & Shulman, 2002), and of the left PPC in directing attention to internal sources of information (e.g., memories; Ciaramelli et al., 2008; Ciaramelli & Moscovitch, 2020), but our data argue for a role of the right PPC in mind-wandering as well. Interestingly, Kajimura et al. (2019) found that while during rest the right PPC (angular gyrus) was involved in the inhibition of mind-wandering and the left PPC in the generation of mind-wandering, during a task both right and left PPC were associated with the generation of mind-wandering. Future studies should investigate whether the left and right PPC play crucial and different roles in mind-wandering, for example testing mind-wandering in patients with lesions to the PPC.

We end by commenting on the limits and future developments of this study. First, we found that tDCS of PPC and mPFC reduced mind-wandering, especially towards the future, but not other forms of off-task thought such as external distractions and task-related thoughts. While this finding is generally consistent with our hypotheses, it is worth noting that future-oriented mind-wandering was the most prominent type of off-task thought in our study, hence the one more likely to be influenced by tDCS. Future studies should try to promote alternative types of off-task experience (e.g., external distractions or task-related thoughts) or past-oriented mind-wandering (e.g., through a memory induction technique), and verify whether inhibiting the activity of mPFC would still result in a most pronounced effect on future-based mindwandering. Another future development of this study would be to move beyond a specific region approach (e.g., inhibiting PPC or mPFC) and consider a network-based approach, for example to assess inter-regional coupling (e.g., Hampstead et al., 2014; Kajimura et al., 2019), or inhibit multiple nodes of distributed brain networks supporting the interaction between external distraction and mind-wandering (e.g., ventral attention network, default network; e.g., Hebscher et al., 2021; Turrini et al., 2023).

To conclude, this study shows that the right PPC and mPFC play a crucial role in directing attention to task-irrelevant internal or external information, though the nature of the involvement in distraction is different in each case. The PPC supports both internal and external distraction, possibly by implementing the disengagement of attention from the current task and its reorienting to salient information, be this a percept or a mental content. The mPFC is uniquely involved in internal distraction, allowing the mind to wander away from the task at hand towards endogenously generated thoughts, mainly about the future. The operation of these two regions, and of the more distributed networks they participate in, supports the adaptive orchestration of attentional resources between the outer and inner (memory) space, warranting perception, introspection, and their interaction.

Conflict of interest statement

The authors declare no competing financial interests.

Acknowledgements

We thank Alberto and Carlo Umiltà for their comments on the paper.
We acknowledge the support of a PRIN grant from the Italian Ministry of Education, University, and Research (PRIN #20174TPEFJ) to EC.

Data availability

Data that support the findings of this study are available upon reasonable request.

References

Andrews-Hanna, J. R., Reidler, J. S., Sepulcre, J., Poulin, R., & Buckner, R. L. (2010). Functional-anatomic fractionation of the brain's default network. *Neuron*, *65*(4), 550–562. https://doi.org/10.1016/j.neuron.2010.02.005

Andrews-Hanna, J. R., Smallwood, J., & Spreng, R. N. (2014). The default network and self-generated thought: component processes, dynamic control, and clinical relevance. *Annals of the New York Academy of Sciences*, *1316*(1), 29–52. https://doi.org/10.1111/nyas.12360

Anelli, F., Avanzi, S., Arzy, S., Mancuso, M., & Frassinetti, F. (2018). Effects of spatial attention on mental time travel in patients with neglect. *Cortex; a journal devoted to the study of the nervous system and behavior*, *101*, 192–205. https://doi.org/10.1016/j.cortex.2018.01.012

Antrobus, J. S., Singer, J. L., & Greenberg, S. (1966). Studies in the stream of consciousness: Experimental enhancement and suppression of spontaneous cognitive processes. *Perceptual and Motor Skills*, *23*(2), 399–417. https://doi.org/10.2466/pms.1966.23.2.399

Arzy, S., Adi-Japha, E., & Blanke, O. (2009). The mental time line: An analogue of the mental number line in the mapping of life events. *Consciousness and Cognition*, *18,* 781–785. https://doi.org/10.1016/j.concog.2009.05.007

Avenanti, A., Paracampo, R., Annella, L., Tidoni, E., & Aglioti, S. M. (2018). Boosting and Decreasing Action Prediction Abilities Through Excitatory and Inhibitory tDCS of Inferior Frontal Cortex. *Cerebral cortex (New York, N.Y. : 1991)*, *28*(4), 1282–1296. https://doi.org/10.1093/cercor/bhx041

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. *Psychological science*, *22*(5), 596–601. https://doi.org/10.1177/0956797611404083

Bernhardt, B. C., Smallwood, J., Tusche, A., Ruby, F. J. M., Engen, H. G., Steinbeis, N., & Singer, T. (2014). Medial prefrontal and anterior cingulate cortical thickness predicts shared individual differences in self-generated thought and temporal discounting. *NeuroImage*, *90*, 290–297. https://doi.org/10.1016/j.neuroimage.2013.12.040

Berryhill, M. E., Phuong, L., Picasso, L., Cabeza, R., & Olson, I. R. (2007). Parietal Lobe and Episodic Memory: Bilateral Damage Causes Impaired Free Recall of Autobiographical Memory. *Journal of Neuroscience*, *27*(52), 14415–14423. https://doi.org/10.1523/JNEUROSCI.4163-07.2007

Bertossi, E., & Ciaramelli, E. (2016). Ventromedial prefrontal damage reduces mind-wandering and biases its temporal focus. *Social cognitive and affective neuroscience*, *11*(11), 1783–1791. https://doi.org/10.1093/scan/nsw099

Bertossi, E., Tesini, C., Cappelli, A., & Ciaramelli, E. (2016). Ventromedial prefrontal damage causes a pervasive impairment of episodic memory and future thinking. *Neuropsychologia, 90*. https://doi.org/10.1016/j.neuropsychologia.2016.01.034

Bertossi, E., Peccenini, L., Solmi, A., Avenanti, A., & Ciaramelli, E. (2017). Transcranial direct current stimulation of the medial prefrontal cortex dampens mind-wandering in men. *Scientific Reports*, *7*. https://doi.org/10.1038/s41598-017-17267-4

Bledowski, C., Prvulovic, D., Hoechstetter, K., Scherg, M., Wibral, M., Goebel, R., & Linden, D. (2004). Localizing P300 Generators in Visual Target and Distractor Processing: A Combined Event-Related Potential and Functional Magnetic Resonance Imaging Study. *The Journal of neuroscience : the official journal of the Society for Neuroscience, 24*, 9353–9360. https://doi.org/10.1523/JNEUROSCI.1897-04.2004

Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision, 10*(4), 433–436. https://doi.org/10.1163/156856897X00357

Buckner, R., Andrews-Hanna, J., & Schacter, D. (2008). The Brain's Default Network. *Annals of the New York Academy of Sciences, 1124*, 1–38. https://doi.org/10.1196/annals.1440.011

Cabeza, R., Ciaramelli, E., Olson, I. R., & Moscovitch, M. (2008). The parietal cortex and episodic memory: An attentional account. *Nature Reviews Neuroscience*, *9*(8), 613–625. PubMed. https://doi.org/10.1038/nrn2459

Cabeza, R., Ciaramelli, E., & Moscovitch, M. (2012). Cognitive contributions of the ventral parietal cortex: an integrative theoretical account. *Trends in Cognitive Science*, 16, 338-52.

Christoff, K., Gordon, A., Smallwood, J., Smith, R., & Schooler, J. (2009). Experience sampling during fMRI reveals default network and executive system contributions to mind wandering. *Proceedings of the National Academy of Sciences of the United States of America, 106*, 8719–8724. https://doi.org/10.1073/pnas.0900234106

Christoff, K., Irving, Z. C., Fox, K. C. R., Spreng, R. N., & Andrews-Hanna, J. R. (2016). Mind-wandering as spontaneous thought: A dynamic framework. *Nature Reviews Neuroscience*, *17*(11), 718–731. https://doi.org/10.1038/nrn.2016.113

Ciaramelli, E., Grady, C. L., & Moscovitch, M. (2008). Top-down and bottom-up attention to memory: A hypothesis (AtoM) on the role of the posterior parietal cortex in memory retrieval. *Neuropsychologia*, *46*(7), 1828–1851. https://doi.org/10.1016/j.neuropsychologia.2008.03.022

Ciaramelli, E., Grady, C., Levine, B., Ween, J., & Moscovitch, M. (2010). Top-down and bottom-up attention to memory are dissociated in posterior parietal cortex: Neuroimaging and and neuropsychological evidence. *The Journal of Neuroscience, 30*(14), 4943–4956. https://doi.org/10.1523/JNEUROSCI.1209-09.2010

Ciaramelli, E., Rosenbaum, R. S., Solcz, S., Levine, B., & Moscovitch, M. (2010). Mental space travel: Damage to posterior parietal cortex prevents egocentric navigation and reexperiencing of remote spatial memories. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 36*(3), 619–634. https://doi.org/10.1037/a0019181

Ciaramelli, E., & Treves, A. (2019). A mind free to wander: Neural and computational constraints on spontaneous thought. *Frontiers in Psychology, 10,* Article 39. https://doi.org/10.3389/fpsyg.2019.00039

Ciaramelli, E., De Luca, F., Monk, A. M., McCormick, C., & Maguire, E. A. (2019). What «wins» in VMPFC: Scenes, situations, or schema? *Neuroscience and Biobehavioral Reviews*, *100*, 208–210. https://doi.org/10.1016/j.neubiorev.2019.03.001

Ciaramelli, E., & Moscovitch, M. (2020). The space for memory in posterior parietal cortex: Re-analyses of bottom-up attention data. *Neuropsychologia*, *146*, 107551. https://doi.org/10.1016/j.neuropsychologia.2020.107551

Ciaramelli, E., De Luca, F., Kwan, D., Mok, J., Bianconi, F., Knyagnytska, V., Craver, C., Green, L., Myerson, J., & Rosenbaum, R. S. (2021). The role of ventromedial prefrontal cortex in reward valuation and future thinking during intertemporal choice. *eLife*, *10*, e67387. https://doi.org/10.7554/eLife.67387

Ciaramelli, E., Anelli, F., & Frassinetti, F. (2021). An asymmetry in past and future mental time travel following vmPFC damage. *Social cognitive and affective neuroscience*, *16*(3), 315–325. https://doi.org/10.1093/scan/nsaa163

Cipolotti, L., Healy, C., Spanò, B., Lecce, F., Biondo, F., Robinson, G., Chan, E., Duncan, J., Shallice, T., & Bozzali, M. (2016). Strategy and suppression impairments after right lateral prefrontal and orbito-frontal lesions. *Brain*, *139*(2), e10–e10. https://doi.org/10.1093/brain/awv269

Corbetta, M., Kincade, J. M., Ollinger, J. M., McAvoy, M. P., & Shulman, G. L. (2000). Voluntary orienting is dissociated from target detection in human posterior parietal cortex. *Nature neuroscience*, *3*(3), 292–297. https://doi.org/10.1038/73009

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience*, *3*(3), 201–215. https://doi.org/10.1038/nrn755

Corbetta, M., Patel, G., & Shulman, G. L. (2008). The reorienting system of the human brain: from environment to theory of mind. *Neuron*, *58*(3), 306–324. https://doi.org/10.1016/j.neuron.2008.04.017

Coulborn, S., Bowman, H., Miall, R. C., & Fernández-Espejo, D. (2020). Effect of tDCS Over the Right Inferior Parietal Lobule on Mind-Wandering Propensity. *Frontiers in human neuroscience*, *14*, 230. https://doi.org/10.3389/fnhum.2020.00230

D'Argembeau A. (2020). Zooming In and Out on One's Life: Autobiographical Representations at Multiple Time Scales. *Journal of cognitive neuroscience*, *32*(11), 2037–2055. https://doi.org/10.1162/jocn_a_01556

de Fockert, J., Rees, G., Frith, C., & Lavie, N. (2004). Neural Correlates of Attentional Capture in Visual Search. *Journal of Cognitive Neuroscience*, *16*(5), 751–759. https://doi.org/10.1162/089892904970762

Di Pellegrino, G., Ciaramelli, E., & Làdavas, E. (2007). The regulation of cognitive control following rostral anterior cingulate cortex lesion in humans. *Journal of cognitive neuroscience*, *19*(2), 275–286. https://doi.org/10.1162/jocn.2007.19.2.275

Downar, J., Crawley, A., Mikulis, D., & Davis, K. (2000). A multimodal cortical network for the detection of changes in the sensory environment. *Nature neuroscience*, *3*, 277–283. https://doi.org/10.1038/72991

Filmer, H. L., Marcus, L. H., & Dux, P. E. (2021). Stimulating task unrelated thoughts: tDCS of prefrontal and parietal cortices leads to polarity specific increases in mind wandering. *Neuropsychologia*, *151*, 107723. https://doi.org/10.1016/j.neuropsychologia.2020.

Fox, K. C. R., Spreng, R. N., Ellamil, M., Andrews-Hanna, J. R., & Christoff, K. (2015). The wandering brain: Meta-analysis of functional neuroimaging studies of mind-wandering and related spontaneous thought processes. *NeuroImage*, *111*, 611–621. https://doi.org/10.1016/j.neuroimage.2015.02.039

Franklin, M., Smallwood, J., & Schooler, J. (2011). Catching the mind in flight: Using behavioral indices to detect mindless reading in real time. *Psychonomic bulletin & review*, *18*, 992–997. https://doi.org/10.3758/s13423-011-0109-6

Friedrich, F. J., Egly, R., Rafal, R. D., & Beck, D. (1998). Spatial attention deficits in humans: a comparison of superior parietal and temporal-parietal junction lesions. *Neuropsychology*, *12*(2), 193–207. https://doi.org/10.1037//0894-4105.12.2.193

Gilbert, S., Frith, C., & Burgess, P. (2005). Involvement of rostral prefrontal cortex in selection between stimulus-oriented and stimulus-independent thought. *The European journal of neuroscience*, *21*, 1423–1431. https://doi.org/10.1111/j.1460-9568.2005.03981.x

Gilbert, S., Spengler, S., Simons, J., Steele, J., Lawrie, S., Frith, C., & Burgess, P. (2006). Functional Specialization within Rostral Prefrontal Cortex (Area 10): A Meta-analysis. *Journal of cognitive neuroscience*, *18*, 932–948. https://doi.org/10.1162/jocn.2006.18.6.932

Hampstead, B. M., Brown, G. S., & Hartley, J. F. (2014). Transcranial direct current stimulation modulates activation and effective connectivity during spatial navigation. *Brain stimulation*, *7*(2), 314–324. https://doi.org/10.1016/j.brs.2013.12.006

Hasenkamp, W., Wilson-Mendenhall, C., Duncan, E., & Barsalou, L. (2011). Mind wandering and attention during focused meditation: A fine-grained temporal analysis of fluctuating cognitive states. *NeuroImage*, *59*, 750–760. https://doi.org/10.1016/j.neuroimage.2011.07.008

Hebscher, M., Kragel, J. E., Kahnt, T., & Voss, J. L. (2021). Enhanced reinstatement of naturalistic event memories due to hippocampal-network-targeted stimulation. *Current biology*, *31*(7), 1428–1437.e5. https://doi.org/10.1016/j.cub.2021.01.027

Heinen, K., Ruff, C. C., Bjoertomt, O., Schenkluhn, B., Bestmann, S., Blankenburg, F., Driver, J., & Chambers, C. D. (2011). Concurrent TMS-fMRI reveals dynamic interhemispheric influences of the right parietal cortex during exogenously cued visuospatial attention. *The European journal of neuroscience*, *33*(5), 991–1000. https://doi.org/10.1111/j.1460-9568.2010.07580.x

Hodsoll, J., Mevorach, C., & Humphreys, G. (2008). Driven to Less Distraction: RTMS of the Right Parietal Cortex Reduces Attentional Capture in Visual Search. *Cerebral cortex (New York, N.Y. : 1991)*, *19*, 106–114. https://doi.org/10.1093/cercor/bhn070

Im, C. H., Park, J. H., Shim, M., Chang, W. H., & Kim, Y. H. (2012). Evaluation of local electric fields generated by transcranial direct current stimulation with an extracephalic reference electrode based on realistic 3D body modeling. *Physics in medicine and biology*, *57*(8), 2137–2150. https://doi.org/10.1088/0031-9155/57/8/2137

Indovina, I., & Macaluso, E. (2007). Dissociation of Stimulus Relevance and Saliency Factors during Shifts of Visuospatial Attention. *Cerebral Cortex*, *17*(7), 1701–1711. https://doi.org/10.1093/cercor/bhl081

Jonides, J., & Yantis, S. (1988). Uniqueness of abrupt visual onset in capturing attention. *Perception & Psychophysics, 43*(4), 346–354. https://doi.org/10.3758/BF03208805

Kajimura, S., & Nomura, M. (2015). Decreasing propensity to mind-wander with Transcranial direct current stimulation. *Neuropsychologia*, *75*. https://doi.org/10.1016/j.neuropsychologia.2015.07.013

Kajimura, S., Kochiyama, T., Nakai, R., Abe, N., & Nomura, M. (2016). Causal relationship between effective connectivity within the default mode network and mind-wandering regulation and facilitation. *NeuroImage*, *133*. https://doi.org/10.1016/j.neuroimage.2016.03.009

Kajimura, S., Kochiyama, T., Abe, N., & Nomura, M. (2019). Challenge to Unity: Relationship Between Hemispheric Asymmetry of the Default Mode Network and Mind Wandering. *Cerebral cortex, 29*(5), 2061–2071. https://doi.org/10.1093/cercor/bhy086

Killingsworth, M. A., & Gilbert, D. T. (2010). A Wandering Mind Is an Unhappy Mind. *Science*, *330*(6006), 932–932. https://doi.org/10.1126/science.1192439

Levinson, D. B., Smallwood, J., & Davidson, R. J. (2012). The Persistence of Thought: Evidence for a Role of Working Memory in the Maintenance of Task-Unrelated Thinking. *Psychological Science*, *23*(4), 375–380. https://doi.org/10.1177/0956797611431465

Mason, M., Norton, M., Van Horn, J., Wegner, D., Grafton, S., & Macrae, C. (2007). Wandering Minds: The Default Network and Stimulus-Independent Thought. *Science (New York, N.Y.)*, *315*, 393–395. https://doi.org/10.1126/science.1131295

McCormick, C., Ciaramelli, E., Luca, F. D., & Maguire, E. A. (2018). Comparing and Contrasting the Cognitive Effects of Hippocampal and Ventromedial Prefrontal Cortex Damage: A Review of Human Lesion Studies. *Neuroscience*, *374*, 295–318. https://doi.org/10.1016/j.neuroscience.2017.07.066

McVay, J. C., & Kane, M. J. (2010). Does mind wandering reflect executive function or executive failure? Comment on Smallwood and Schooler (2006) and Watkins (2008). *Psychological bulletin*, *136*(2), 188–197. https://doi.org/10.1037/a0018298

Mevorach, C., Humphreys, G. W., & Shalev, L. (2006). Opposite biases in salience-based selection for the left and right posterior parietal cortex. *Nature neuroscience*, *9*(6), 740–742. https://doi.org/10.1038/nn1709

Mittner, M., Boekel, W., Tucker, A., Turner, B., Heathcote, A., & Forstmann, B. (2014). When the Brain Takes a Break: A Model-Based Analysis of Mind Wandering. *The Journal of neuroscience : the official journal of the Society for Neuroscience*, *34*, 16286–16295. https://doi.org/10.1523/JNEUROSCI.2062-14.2014

Mittner, M., Hawkins, G. E., Boekel, W., & Forstmann, B. U. (2016). A Neural Model of Mind Wandering. *Trends in cognitive sciences*, *20*(8), 570–578. https://doi.org/10.1016/j.tics.2016.06.004

Monti, A., Cogiamanian, F., Marceglia, S., Ferrucci, R., Mameli, F., Mrakic-Sposta, S., Vergari, M., Zago, S., & Priori, A. (2008). Improved naming after transcranial direct current stimulation in aphasia. *Journal of neurology, neurosurgery, and psychiatry, 79*(4), 451–453. https://doi.org/10.1136/jnnp.2007.135277

Mrazek, M., Phillips, D., Franklin, M., Broadway, J., & Schooler, J. (2013). Young & restless: Validation of the Mind-Wandering Questionnaire (MWQ) reveals disruptive impact of mind-wandering for youth. *Frontiers in psychology*, *4*, 560. https://doi.org/10.3389/fpsyg.2013.00560

Nitsche, M., Fricke, K., Henschke, U., Schlitterlau, A., Liebetanz, D., Lang, N., Henning, S., Tergau, F., & Paulus, W. (2003). Pharmacological Modulation of Cortical Excitability Shifts Induced by Transcranial Direct Current Stimulation in Humans. *The Journal of physiology*, *553*, 293–301. https://doi.org/10.1113/jphysiol.2003.049916

Nitsche, M. A., Cohen, L. G., Wassermann, E. M., Priori, A., Lang, N., Antal, A., Paulus, W., Hummel, F., Boggio, P. S., Fregni, F., & Pascual-Leone, A. (2008). Transcranial direct current stimulation: State of the art 2008. *Brain Stimulation*, *1*(3), 206–223. https://doi.org/10.1016/j.brs.2008.06.004

Posner, M. I. (1980). Orienting of Attention. *Quarterly Journal of Experimental Psychology*, *32*(1), 3–25. https://doi.org/10.1080/00335558008248231

O'Callaghan, C., Shine, J. M., Hodges, J. R., Andrews-Hanna, J. R., & Irish, M. (2019). Hippocampal atrophy and intrinsic brain network dysfunction relate to alterations in mind wandering in neurodegeneration. *Proceedings of the National Academy of Sciences of the United States of America*, *116*(8), 3316–3321. https://doi.org/10.1073/pnas.1818523116

Philippi, C. L., Bruss, J., Boes, A. D., Albazron, F. M., Deifelt Streese, C., Ciaramelli, E., Rudrauf, D., & Tranel, D. (2021). Lesion network mapping demonstrates that mind-wandering is associated with the default mode network. *Journal of neuroscience research*, *99*(1), 361–373. https://doi.org/10.1002/jnr.24648

Schooler, J., Smallwood, J., Christoff, K., Handy, T., Reichle, E., & Sayette, M. (2011). Meta-awareness, perceptual decoupling and the wandering mind. *Trends in cognitive sciences*, *15*, 319–326. https://doi.org/10.1016/j.tics.2011.05.006

Seli, P., Kane, M. J., Smallwood, J., Schacter, D. L., Maillet, D., Schooler, J. W., & Smilek, D. (2018). Mind-Wandering as a Natural Kind: A Family-Resemblances View. *Trends in cognitive sciences*, *22*(6), 479–490. https://doi.org/10.1016/j.tics.2018.03.010

Smallwood, J. M., Baracaia, S. F., Lowe, M., & Obonsawin, M. (2003). Task unrelated thought whilst encoding information. *Consciousness and cognition*, *12*(3), 452–484. https://doi.org/10.1016/s1053-8100(03)00018-7

Smallwood, J., & Schooler, J. W. (2006). The restless mind. *Psychological Bulletin, 132*(6), 946–958. https://doi.org/10.1037/0033-2909.132.6.946

Smallwood, J., Fishman, D. J., & Schooler, J. W. (2007). Counting the cost of an absent mind: mind wandering as an underrecognized influence on educational performance. *Psychonomic bulletin & review*, *14*(2), 230–236. https://doi.org/10.3758/bf03194057

Smallwood, J., & Schooler, J. W. (2015). The science of mind wandering: empirically navigating the stream of consciousness. *Annual review of psychology*, *66*, 487–518. https://doi.org/10.1146/annurev-psych-010814-015331

Stawarczyk, D., Majerus, S., Maquet, P., & D'Argembeau, A. (2011). Neural correlates of ongoing conscious experience: both task-unrelatedness and stimulus-independence are related to default network activity. *PloS one*, *6*(2), e16997. https://doi.org/10.1371/journal.pone.0016997

Stawarczyk, D., Majerus, S., Catale, C., & D'Argembeau, A. (2014). Relationships between mind-wandering and attentional control abilities in young adults and adolescents. *Acta psychologica*, *148*, 25–36. https://doi.org/10.1016/j.actpsy.2014.01.007

Stawarczyk, D., & D'Argembeau, A. (2015). Neural correlates of personal goal processing during episodic future thinking and mind-wandering: An ALE meta-analysis. *Human brain mapping*, *36*(8), 2928–2947. https://doi.org/10.1002/hbm.22818

Stevens, M. C., Calhoun, V. D., & Kiehl, K. A. (2005). Hemispheric differences in hemodynamics elicited by auditory oddball stimuli. *NeuroImage*, *26*(3), 782–792. https://doi.org/10.1016/j.neuroimage.2005.02.044

Stuss, D., Binns, M., Murphy, K., & Alexander, M. (2002). Dissociation within the anterior attentional system: Effects of task complexity and irrelevant information on reaction time speed and accuracy. *Neuropsychology*, *16*, 500–513. https://doi.org/10.1037/0894-4105.16.4.500

Stuss, D., Alexander, M., Shallice, T., Picton, T., Binns, M., Macdonald, R., Borowiec, A., & Katz, D. (2005). Multiple frontal systems controlling response speed. *Neuropsychologia*, *43*, 396–417. https://doi.org/10.1016/j.neuropsychologia.2004.06.010

Teasdale, J., Dritschel, B., Taylor, M., Proctor, L., Lloyd, C., Nimmo-Smith, I., & Baddeley, A. (1995). Stimulus-independent thought depends on central executive resources. *Memory & cognition*, *23*, 551–559. https://doi.org/10.3758/BF03197257

Theeuwes J. (1991). Exogenous and endogenous control of attention: the effect of visual onsets and offsets. *Perception & psychophysics*, *49*(1), 83–90. https://doi.org/10.3758/bf03211619

Townsend, J., & Ashby, F. G. (1978). Methods of modeling capacity in simple processing systems. *Cogn. Theory*, *3*, 200–239.

Townsend, J., & Ashby, F. (1983). The Stochastic Modeling of Elementary Psychological Processes. In *The American Journal of Psychology* (Vol. 98). https://doi.org/10.2307/1422636

Turrini, S., Fiori, F., Chiappini, E., Lucero, B., Santarnecchi, E., & Avenanti, A. (2023). Cortico-cortical paired associative stimulation (ccPAS) over premotor areas affects local circuitries in the human motor cortex via Hebbian plasticity. Neuroimage, 271: 120027.

Unsworth, N., & McMillan, B. D. (2014). Similarities and differences between mind-wandering and external distraction: a latent variable analysis of lapses of attention and their relation to cognitive abilities. *Acta psychologica*, *150*, 14–25. https://doi.org/10.1016/j.actpsy.2014.04.001

Wagner, A. D., Shannon, B. J., Kahn, I., & Buckner, R. L. (2005). Parietal lobe contributions to episodic memory retrieval. *Trends in Cognitive Sciences*, *9*(9), 445–453. https://doi.org/10.1016/j.tics.2005.07.001

Yantis, S., & Jonides, J. (1990). Abrupt Visual Onsets and Selective Attention: Voluntary Versus Automatic Allocation. *Journal of experimental psychology*. *Human perception and performance*, *16*, 121–134. https://doi.org/10.1037/0096-1523.16.1.121

Ziaei, M., Samrani, G., & Persson, J. (2018). Age differences in the neural response to emotional distraction during working memory encoding. *Cognitive, Affective, & Behavioral Neuroscience*, *18*. https://doi.org/10.3758/s13415-018-0610-8

Figure Captions

Figure 1. Experimental paradigm and design. Participants performed a visual search task while their thoughts were occasionally probed for mind-wandering both before and after receiving **cathodal tDCS** to the right posterior parietal cortex (PPC) or medial prefrontal cortex (mPFC).

Figure 2. Distractor effect ($iRTs_{Singleton\ distractor} - iRTs_{Standard}$) by participant group and session. Error bars indicate standard errors of the mean. *$p < 0.05$. Dots indicate the performance of individual subjects.

Figure 3. Target effect ($iRTs_{Standard} - iRTs_{Singleton\ target}$) by participant group and session. Error bars indicate standard errors of the mean. Dots indicate the performance of individual subjects.

Figure 4. Change index (post-tDCS – pre-tDCS) for Internal Thoughts, External Distractions and Task Reflections by Stimulation Group. Error bars indicate the standard error of the mean. *$p<0.05$. Dots indicate the performance of individual subjects.

Figure 5. Mean difference in the future thought index between the pre-tDCS and the post-tDCS session by stimulation group. Error bars indicate the standard error of the mean. *$p<0.05$. Dots indicate the performance of individual subjects.

Supplementary Materials

For

The role of posterior parietal cortex and medial prefrontal cortex in distraction and mind-wandering

Luca Giacometti Giordani[1], Andrea Crisafulli[1], Giovanni Cantarella[1,2], Alessio Avenanti[1,2], and Elisa Ciaramelli[1,2,*]

Supplementary Methods

Working Memory Task

Before starting the experimental sessions, all participants were evaluated on their working memory capacity, an aspect of executive functioning linked to mind-wandering (Levinson et al., 2012; Smallwood & Schooler, 2006; Teasdale et al., 1995), with a 3-back task (Zimmerman & Fimm, 2002). The task required to monitor a series of 100 digit stimuli (from 1 to 8), and signal whether the number currently presented matched the number presented 3 trials earlier. Each number was presented for 2 s, followed by a fixation cross lasting 1.5 s.

Mind Wandering Questionnaire

Following the working memory task, participants were administered the Italian version of the Mind Wandering Questionnaire (MWQ; Mrazek et al., 2013), which assesses the self-reported frequency of attentional shifts from an external activity towards the inner world (e.g., ‘while reading, I find I haven’t been thinking about the text and must therefore read it again’). The MWQ was originally designed to assess attention and distraction in university students, and therefore it was particularly suited to our sample. The questionnaire consisted of 5 items, whose response range was from 1 to 6. The total score ranges from 5 to 30, with higher scores indicating a higher propensity towards mind-wandering.

Supplementary Results

Relation between mind-wandering and visual search

We investigated whether mind-wandering influenced performance on the visual search task. We focused on the pre-tDCS session, as the different tDCS stimulation delivered to participant groups may alter the relation between mind-wandering and visual search. For each individual, we computed the median thought intensity reported at the VAS in association with thought probes, and divided trials into those attracting low vs. high levels of off-task thought using a median-split. Then, for each thought probe trial and individual, we computed the mean RTs and accuracy relative to the 15 visual search trials preceding the thought probe (collapsing across trial types). We then compared RTs and accuracy associated with trials preceding high vs. low intensity off-task thought trials across participant groups, using paired-sampled t tests. Participants were less accurate (M = 0. 98, SD = 0.02; M = 0.99, SD = 0.02; $t_{64} = -1.95$; p = 0.03) and faster (M = 622 ms, SD = 71; M = 629 ms, SD = 69; $t_{64} = -1.68$; p = 0.049) in visual search trials that preceded reports of high vs. low levels of off-task thought, compatible with a tendency towards more impulsive responding. Because mind-wandering affected speed and accuracy in opposite ways, no significant difference was detected on the iRTs for trials preceding reports of high vs. low off-task thought (p = 0.15).

Supplementary Tables

Supplementary Table 1. Mean mind-wandering scores (and SD) for internal thoughts by temporal focus, participant group, and visual search condition. PPC = posterior parietal cortex; mPFC = medial prefrontal cortex.

	Past		**Future**		**Present**		**Atemporal**	
	pre-tDCS	*post-tDCS*	*pre-tDCS*	*post-tDCS*	*pre-tDCS*	*post-tDCS*	*pre-tDCS*	*post-tDCS*
Sham group	48 (62)	50 (58)	55 (85)	159 (124)	75 (90)	78 (78)	49 (83)	87 (98)
PPC group	70 (75)	43 (64)	72 (64)	109 (104)	53 (76)	70 (86)	63 (94)	78 (90)
mPFC group	64 (103)	81 (95)	81 (87)	112 (97)	65 (66)	58 (73)	80 (102)	95 (90)