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

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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.

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 and 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 and 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

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one location but it unexpectedly appears at another (Posner, 1980; Corbetta et al., 2000; Indovina and 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 and 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 et al. (2008) 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 and 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 cortices, 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 and 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 and 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 and 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 and Treves, 2019), allowing the flexible switching of attention between external and internal stimuli, possibly via interactions with 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, 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. (2008), 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 Fig. 1).

If the right PPC is primarily implicated in directing attention to the external environment (Corbetta and 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, see also Kajimura et al., 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., 2011; 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 and 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 and 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

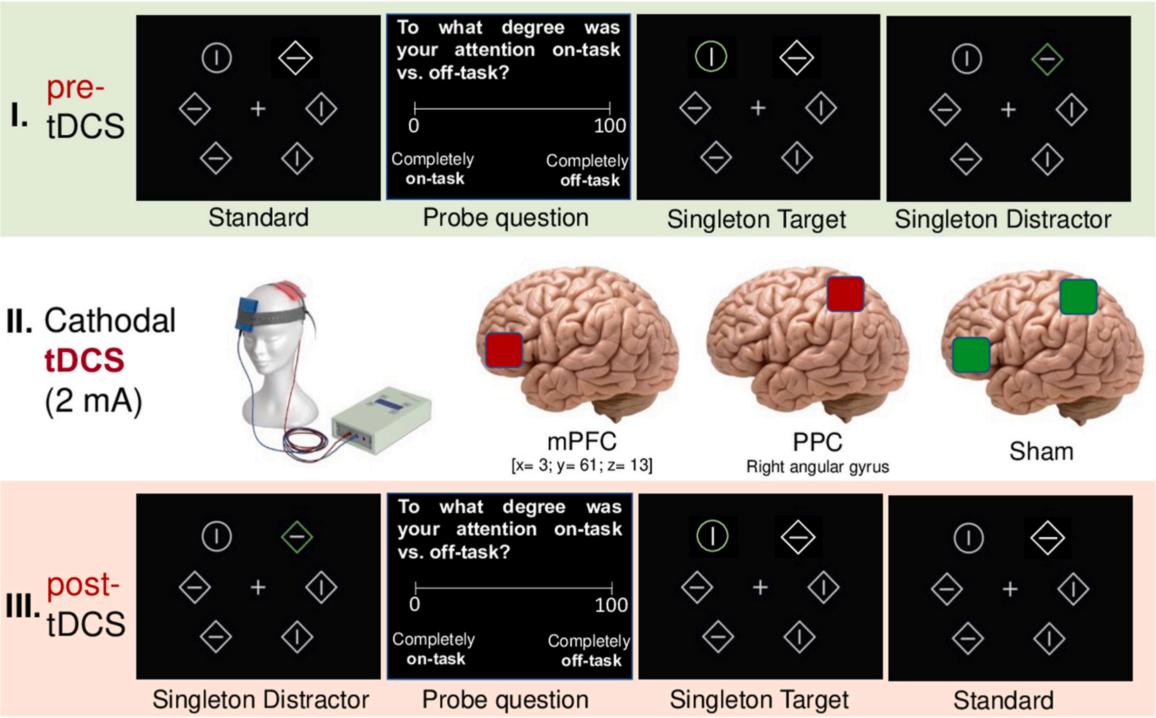

Fig. 1. Experimental paradigm and design. Participants performed a visual search task while their thoughts were occasionally probed for mind-wandering both before and after receiving cathodal tDCS to the right posterior parietal cortex (PPC) or medial prefrontal cortex (mPFC).

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 and 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 and 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 (Bertossi et al., 2017; Kajimura and Nomura, 2015; Kajimura et al., 2019). Participant groups were matched for working memory performance (p > 0.27, η 2 < 0.041 both for accuracy and RTs) and baseline propensity to mind-wander at the Mind Wandering questionnaire (MWQ; p = 0.36; η 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; η p2 = 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 the 1964 Declaration of Helsinki.

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 (5 × 5 cm) and anodal (5 × 7 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., 2008; 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 Fig. 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 s 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 s 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 min each), one before and one after the tDCS stimulation, with occasional thought probes aimed at assessing mind-wandering (see Fig. 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 (Fig. 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 stimulus-independent and task-unrelated (Stawarczyk et al., 2011), were used as an index of attention towards task-irrelevant *internal* information (mind-wandering).

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.

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

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)

distractor compared to the other conditions (See Table 3).

For data analysis, RTs and accuracy relative to each singleton condition were combined in an 'inverse efficacy score', computed as iRTs = RTs/accuracy (Townsend and 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).

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., 2008) 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 ($F_{2,124} = 231.03$; $p = 0.0001$; η p2 = 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 ($F \leq 1.72$; $p \geq 0.19$; η p2 $\leq$ 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 = iRTsSingleton distractor – iRTsStandard), separately for the pre- and post-tDCS sessions (see Fig. 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 × Session interaction ($F_{2,62} = 3.88$; $p = 0.03$; η p2 = 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 = iRTsStandard – iRTsSingleton target) evinced instead no significant effects ($F \leq 2.30$; $p > 0.15$; η p2 $\leq$ 0.10 in all cases; see Fig. 3).

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 (internal thoughts, external distractions, task-related thoughts) and temporal focus. In particular, internal thoughts (mind-wandering) were indicative of internal attention (see Table 5).

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)

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)

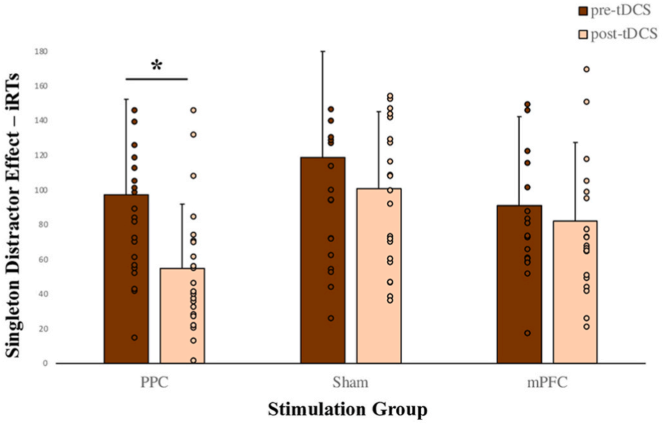

Fig. 2. Distractor effect (iRTsSingleton distractor – iRTsStandard) by participant group and session. Error bars indicate standard errors of the mean. *p < 0.05. Dots indicate the performance of individual subjects.

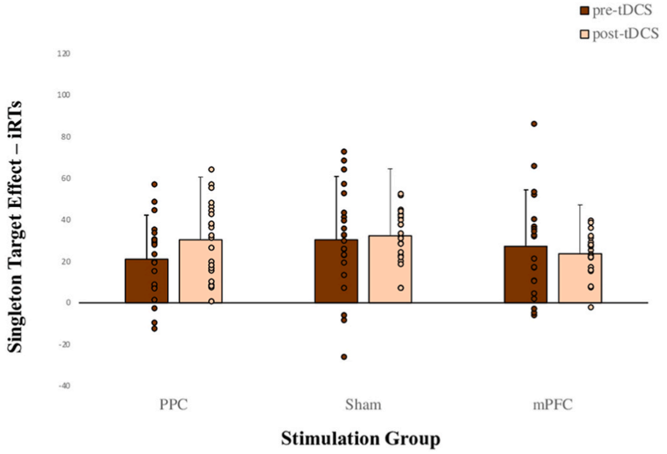

Fig. 3. Target effect (iRTsStandard – iRTsSingleton target) by participant group and session. Error bars indicate standard errors of the mean. Dots indicate the performance of individual subjects.

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

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)

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).

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 Fig. 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.

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., 2021a,b) and past-oriented self--projection (Anelli et al., 2018), 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

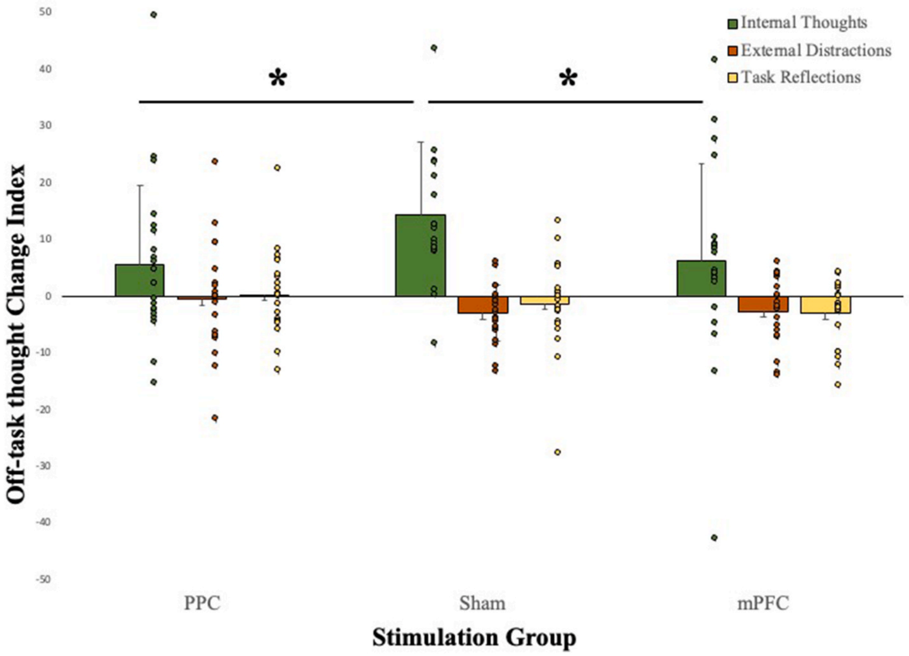

Fig. 4. Change index (post-tDCS – pre-tDCS) for Internal Thoughts, External Distractions and Task Reflections by Stimulation Group. Error bars indicate the standard error of the mean. *$p < 0.05$. Dots indicate the performance of individual subjects.

session from that at the post-tDCS session and compared this difference score across participant groups (see Fig. 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 and Ciaramelli, 2016).

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 and Gilbert, 2010; Smallwood and 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.

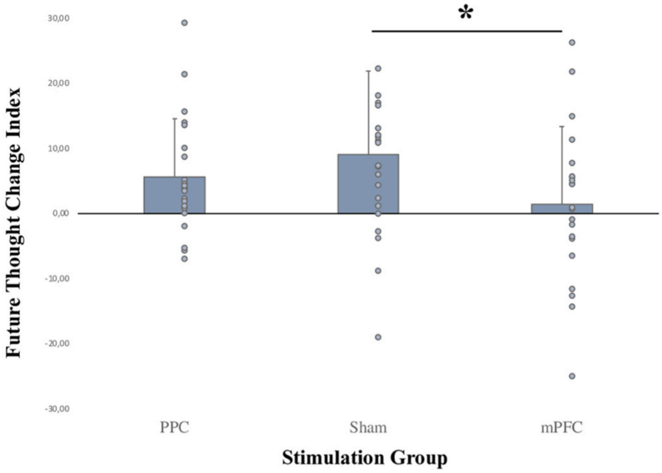

Fig. 5. Mean difference in the future thought index between the pre-tDCS and the post-tDCS session by stimulation group. Error bars indicate the standard error of the mean. *$p < 0.05$. Dots indicate the performance of individual subjects.

As a core region of the default network (Stawarczyk 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 and 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. (2016), 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., 2021b) 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 and 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 and 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 and 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., 2021b). 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 and 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 finding aligns with recent models of attention maintaining 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 and 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., 2010a,b), 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 and Shulman, 2002), and of the left PPC in directing attention to internal sources of information (e.g., memories; Ciaramelli et al., 2008; Ciaramelli and 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, and, therefore, the one more likely to be reduced 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 reduction of future-based mind-wandering. Another future development of this study would be to move beyond a region-specific 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.

Credit author statement

LGG, AC, AA, and EC developed the study concept and contributed to the study design. LGG and AC collected the data. LGG, GC, and EC analyzed the data. All authors contributed to the interpretation of the findings. LGG and GC drafted the manuscript. AA and EC revised the manuscript and all authors approved its final version.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.neuropsychologia.2023.108639.

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