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When attention wanders: Pupillometric signatures of fluctuations in external attention

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ABSTRACT

Attention is not always directed to events in the external environment. On occasion our thoughts wander to people and places distant from the here and now. Sometimes, this lack of external attention can compromise ongoing task performance. In the current study we set out to understand the extent to which states of internal and external attention can be determined using pupillometry as an index of ongoing cognition. In two experiments we found that periods of slow responding were associated with elevations in the baseline pupil signal over three and a half seconds prior to a behavioural response. In the second experiment we found that unlike behavioural lapses, states of off-task thought, particularly those associated with a focus on the past and with an intrusive quality, were associated with reductions in the size of the pupil over the same window prior to the probe. These data show that both states of large and small baseline pupil size are linked to states when attention is not effectively focused on the external environment, although these states have different qualities. More generally, these findings illustrate that subjective and objective markers of task performance may not be equivalent and underscore the importance of developing objective indicators that can allow these different states to be understood.

1. Introduction

Attention is not always focused on the external environment; experiences like mind-wandering and daydreaming illustrate situations when cognition is generated based on our factual knowledge of the world, and episodic memories about the people we know and the places we have visited over the course of our lives (Smallwood, 2013; Smallwood & Schooler, 2015; Smallwood et al., 2016). Although we now know that these experiences make contributions to our well-being (Killingsworth & Gilbert, 2010; Poerio, Totterdell, & Miles, 2013), can arise either intentionally or spontaneously (Seli, Risko, & Smilek, 2016), and can compromise ongoing performance (Mcvay & Kane, 2009; Smallwood, McSpadden, & Schooler, 2008), the intrinsic nature of these experiences has hindered our capacity to understand their contributions to the human condition.

One barrier to the investigation of self-generated states is a reliance on measures of self-report. Introspective evidence allows the internal landscape of personal experience to be described, and participants have been shown to be reliable assessors of their task focus (Mittner, Hawkins, Boekel, & Forstmann, 2016; Seli et al., 2015). Nonetheless, the requirement that participants must explicitly reflect on the contents of their experience makes it possible that results that are generated in this fashion may alter the nature of the experiences that are being investigated (Konishi & Smallwood, 2016). One way to understand, and ultimately overcome, these issues, is through the development of indirect markers that could be used as a proximal measure for the occurrence of self-generated thoughts. The current study attempts to address this issue using pupillometry as a covert marker for ongoing cognitive processing.

Prior studies have found that when the baseline diameter of pupils is unusually small or large, attention is not always effectively focused on the external environment. For example, momentary lapses in attention, as indexed by slow response times or errors in performance, are preceded by periods of both large and small baseline pupil size (Gilzenrat, Nieuwenhuis, Jepma, & Cohen, 2010; Smallwood et al., 2011, 2012; Van Den Brink, Murphy, & Nieuwenhuis, 2016; Van Orden, Jung, & Makeig, 2000). A similar pattern has been observed across studies of mind-wandering, with some finding increased pupil diameter co-

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occurring with self-reports of off task/mind-wandering episodes (Franklin, Broadway, Mrazek, Smallwood, & Schooler, 2013), while others have found the reverse (Grandchamp, Braboszcz, & Delorme, 2014). A more recent study (Unsworth & Robison, 2016), which differentiated between types of off task states, found increased baseline pupil size before reports of external distraction and reduced pupil size before both reports of mind wandering episodes and inattentiveness. It is widely accepted that pupillometry provides an indirect measure of arousal and of locus coeruleus (LC) activity (Aston-Jones & Cohen, 2005; Morad, Lemberg, Yofe, & Dagan, 2000; Murphy, Robertson, Balsters, & O'connell, 2011; Stanners, Coulter, Sweet, & Murphy, 1979; Wilhelm, Wilhelm, Lüdtke, Streicher, & Adler, 1998; Yoss, Moyer, & Hollenhorst, 1970), and that arousal/LC activity have a known relation to performance and attention (Aston-Jones, Rajkowski, & Cohen, 1999; Yerkes & Dodson, 1908), with extreme levels of arousal linked to drowsiness or high distractibility. Moreover, catecholamines such as noradrenaline which are linked to the LC, are thought to adjust the gain on neural processing across the cortex, and at moderate levels help gate sensory processing in a goal related manner and thus ensuring cognitive and behavioural stability (Hauser, Fiore, Moutoussis, & Dolan, 2016). It thus seems plausible that states of optimal focus may be indicated by moderate levels of arousal, with extremely large or small pupils indicating situations when attention is not engaged with the external environment to the same degree (Aston-Jones & Cohen, 2005; Smallwood et al., 2011). Moreover, the pupil signal may provide important descriptive information on how the mind shifts between these states (Hauser et al., 2016; Mittner et al., 2016).

It has been suggested that understanding the relationship between self-generated thought and other aspects of neurocognitive functioning can depend on the *content* of individuals' experiences (Smallwood & Andrews-Hanna, 2013). For example, studies have found that when experience is focused on events from the past, this is often associated with lower levels of happiness (Poerio et al., 2013; Ruby, Smallwood, Engen, & Singer, 2013, Ruby, Smallwood, Sackur, & Singer, 2013; Smallwood & O'Connor, 2011). By contrast, thoughts about the future, but not the past, have been linked to reductions in levels of social stress (Engert, Smallwood, & Singer, 2014) and may contribute to the processes through which people consolidate personal goals (Medea et al., 2016). Neurocognitive investigations have also highlighted differences between these classes of experiences. Self-generated thoughts about the past were linked to higher connectivity between lateral temporal lobe regions and the hippocampus, reflecting the heightened role of episodic memory when we retrospect, and relatively greater decoupling between medial prefrontal cortex and medial visual cortex than for individuals who tend to think more about the future (Smallwood et al., 2016). Together, these observations support the hypothesis that the *content* of self-generated thought in part determines its relationship to other neurocognitive measures.

As well as taking into account the content of self-generated thought, it is important to consider the *context* in which self-generated thought occurs (Smallwood & Andrews-Hanna, 2013). Studies have shown that, although participants' executive control capacity relates to lower levels of off-task thought when tasks are complex (Mcvay & Kane, 2009; Unsworth & Robison, 2016), the relationship can reverse when tasks are less demanding (Bernhardt et al., 2014; Kane et al., 2007; Levinson, Smallwood, & Davidson, 2012; Rummel & Boywitt, 2014; Smallwood, Ruby, & Singer, 2013). Indeed, task demands modulate different types of off-task thought, with a focus on the future more common in easy tasks (Ruby, Smallwood, Engen et al., 2013, Ruby, Smallwood, Sackur et al., 2013; Smallwood, Nind, & O'Connor, 2009). Under these conditions mind-wandering is described as more intentional (Seli, Risko, et al., 2016; Seli, Risko, Smilek, & Schacter, 2016), and is less likely to be detrimental to task performance (Thomson, Seli, Besner, & Smilek, 2014). It is often assumed that self-generated thought is more common during tasks that lack complex demands (Teasdale, Proctor, Lloyd, & Baddeley, 1993) because there is a greater availability of cognitive resources to devote to self-generated thought. Together these lines of evidence suggest that understanding the context in which self-generated occurs can be important in understanding its neurocognitive basis.

The current study aims to elucidate the relationship between pupil diameter and the extent to which attention is deployed to the external environment. We measured pupil diameter in the context of a paradigm in which we manipulated the degree of external task focus by means of the addition of a working memory load (see Fig. 1). We have previously used this paradigm to vary the amount of attention that participants devote to an ongoing task, a manipulation that is reflected in the speed and effectiveness with which decisions are made, as well as in changes in reports of task focus. In a prior study we acquired functional magnetic resonance imaging data during this task and found that performance of the easy task is accompanied by greater engagement of regions of the default mode network (Konishi, McLaren, Engen, & Smallwood, 2015), a neural system important in self-generated thought (Allen et al., 2013; Christoff, Gordon, Smallwood, Smith, & Schooler, 2009; Christoff, Irving, Fox, Spreng, & Andrews-Hanna, 2016; Fox, Spreng, Ellamil, Andrews-Hanna, & Christoff, 2015; Mason et al., 2007; Stawarczyk, Majerus, Maquet, & D'Argembeau, 2011).

Using this paradigm, we conducted two experiments on healthy participants in which we acquired measures of pupil diameter while they performed alternating blocks of the 0-back and 1-back versions of this paradigm. We acquired two different indicators of the focus of attention. In Experiment 1 we acquired measures of behavioural task performance, and in Experiment 2 we also measured the content of ongoing thought using Multi-Dimensional Experience Sampling (MDES; Karapanagiotidis, Bernhardt, Jefferies, & Smallwood, 2016; Medea et al., 2016; Smallwood & Schooler, 2015; Smallwood et al., 2016). We measured both subjective and objective indicators of attention to explore whether they had the same signature in terms of baseline pupil size. Our motivation for measuring subjective indicators of attention only in the second experiment was to address the concern that the act of introspecting on experience would alter the nature of any pupil-behaviour relationships observed in the first experiment.

Although we also examined evoked responses in the pupil signal, the primary focus of our analysis was baseline pupil diameter, given prior work indicating that this measure provides an index of whole brain neural gain that describes the stability of cognition at a given moment (Hauser et al., 2016; Mittner et al., 2016). Importantly, while the content of mind wandering episodes has been investigated with behavioural and fMRI measures (Gorgolewski et al., 2014; Karapanagiotidis et al., 2016; Medea et al., 2016; Smallwood et al., 2016), previous pupillometric studies only differentiated between states of on-task or off-task (or within off-task states, such as mind wandering or external distraction), but did not explore content-related questions (e.g. Franklin et al., 2013; Grandchamp et al., 2014; Smallwood et al., 2011; Unsworth & Robison, 2016). Given evidence of neural differences associated with different forms of content during mind-wandering, we sought to re-evaluate the links between on-going experience and the pupil signal to explore which aspects of experiential content it reflects. In this way, our study is the first to explore the hypothesis that physiological changes may underpin differences within the content of experience during the