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Thinking about thinking: Neural mechanisms and effects on memory

Corinna Bonhage [a,b,*,1], Friederike Weber [c,1], Cornelia Exner [c], Philipp Kanske [d]

[a] Neurolinguistics Department, Institute of Cognitive Science, University of Osnabruck, Germany
[b] Department of Neuropsychology, Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany
[c] Department of Clinical Psychology and Psychotherapy, University of Leipzig, Germany
[d] Department of Social Neuroscience, Max Planck Institute for Human Cognitive and Brain Sciences, Leipzig, Germany

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It is a well-established finding that memory encoding is impaired if an external secondary task (e.g. tone discrimination) is performed simultaneously. Yet, while studying we are also often engaged in internal secondary tasks such as planning, ruminating, or daydreaming. It remains unclear whether such a secondary internal task has similar effects on memory and what the neural mechanisms underlying such an influence are. We therefore measured participants' blood oxygenation level dependent responses while they learned word-pairs and simultaneously performed different types of secondary tasks (i.e., internal, external, and control). Memory performance decreased in both internal and external secondary tasks compared to the easy control condition. However, while the external task reduced activity in memory-encoding related regions (hippocampus), the internal task increased neural activity in brain regions associated with self-reflection (anterior medial prefrontal cortex), as well as in regions associated with performance monitoring and the perception of salience (anterior insula, dorsal anterior cingulate cortex). Resting-state functional connectivity analyses confirmed that anterior medial prefrontal cortex and anterior insula/dorsal anterior cingulate cortex are part of the default mode network and salience network, respectively. In sum, a secondary internal task impairs memory performance just as a secondary external task, but operates through different neural mechanisms.

Introduction

Numerous studies have shown that memory performance suffers if an *external* secondary task (e.g. listening tasks) is performed during encoding (e.g. Murdock, 1965; Baddeley et al., 1984; Naveh-Benjamin et al., 2003). However, we also engage in *internal* secondary tasks, such as planning, ruminating, or daydreaming (Kane et al., 2007; Killingsworth and Gilbert, 2010). The effects that such a preoccupation with one's own thoughts has on memory performance are poorly understood despite the high prevalence of an internal attentional focus of about one-third of the waking time (Killingsworth and Gilbert, 2010). The incidence rate is even further increased in some clinical groups, such as obsessive-compulsive or major depressive disorder (Wells and Matthews, 1996; Wells, 2000; Huffziger et al., 2009), which also show memory impairments (Kuelz et al., 2004; Trivedi and Greer, 2013). This raises the hypothesis that the preoccupation with internal processes directly impairs memory encoding (Exner et al., 2009; Smallwood et al., 2007). We therefore aim at studying the consequences of a preoccupation with one's own thoughts by asking (1) whether or not an *internal* secondary task impairs memory encoding in a similar fashion as an *external* secondary task, and (2) what the neural mechanisms underlying the impairments due to internal versus external secondary task performance are.

So far, several neuroimaging studies investigating the processes underlying memory impairment due to divided attention asked participants to memorize items and simultaneously perform an external secondary task, such as auditory tone discrimination. Such external secondary tasks impaired memory performance by interfering with semantic processing of the items (i.e. attenuated activation in inferior frontal gyrus) (Shallice et al., 1994; Fletcher et al., 1995; Iidaka et al., 2000; Anderson et al., 2000), disrupting effective encoding processes (i.e. attenuation of subsequent memory effects in the hippocampus) (Kensinger et al., 2003; Uncapher and Rugg, 2008), or by competing with the primary memory task for general processing resources (i.e. executive processes, dorsolateral PFC) (Fletcher et al., 1998; Uncapher and Rugg, 2005).

So far, memory research has largely neglected *internal* secondary tasks, most likely because it is difficult to experimentally manipulate internal processes. A recent approach has been to assess whether or not task-unrelated thoughts surface during episodic memory encoding (Maillet and Rajah, 2014b), providing first tentative evidence that memory performance drops in trials where participants experience

* Corresponding author at: University of Osnabruck, Institute of Cognitive Science, Albrechtstr. 28, 49076 Osnabrück, Germany.
E-mail address: corinna.bonhage@uos.de (C. Bonhage).
[1] Shared first authorship.

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task-unrelated thoughts (i.e., mind wandering, task-relevant interferences, or internal/external distractions) compared to trials where they were focused on the task. However, although this approach is ecologically valid, it (a) subsumes internally and externally focused cognitive processes under the term “task-unrelated thoughts” and (b) does not experimentally manipulate or control the internal processes. In order to compare the effects of internal versus external secondary tasks on memory encoding, it was necessary to identify a solely internally-focused secondary process that can be experimentally varied: heightened cognitive self-consciousness.

Heightened cognitive self-consciousness is defined as the tendency to monitor and be preoccupied with one's own thoughts (Cartwright-Hatton and Wells, 1997) — it refers to an ongoing process, a “state of mind” in which the subjects find themselves. More specifically, heightened cognitive self-consciousness can be understood as a state of heightened awareness of thinking (Janeck et al., 2003) (e.g. “Am I thinking about work, while reading a book and actually trying not to worry about work?”). In terms of brain effort, it can be considered an ongoing, parallel cognitive process, which, in contrast to mind wandering (cf.Mrazek et al., 2012), is not suppressed during external cognitive challenges such as working memory tasks and thus qualifies as an internal secondary task for the present experiment. The definition of heightened cognitive self-consciousness is clearly more restricted than the conglomerate of concepts under the term “task-unrelated thought”, which comprises mind wandering, task-related interfering thoughts, as well as external distraction (e.g. due to scanner noise) in the study by Maillet and colleagues.

Most importantly, in contrast to other mental activities classified as preoccupation with one's own thoughts such as for example mind wandering (Smallwood, 2013), heightened cognitive self-consciousness can be induced reliably through experimental manipulation (Weber et al., 2014). In a behavioral study, we recently probed a thought-monitoring task as an internal secondary task that induced heightened cognitive self-consciousness and yielded first evidence that internal secondary tasks might indeed impair encoding similarly to external secondary tasks (Weber et al., 2014). Therefore, using heightened cognitive self-consciousness enabled us to directly compare the neurophysiological effects of external versus internal secondary tasks during memory encoding.

Hypotheses

The present study aimed to characterize the neural correlates of memory impairment caused by heightened cognitive self-consciousness and investigating whether or not these mechanisms differ from processes underlying memory impairment caused by an external secondary task.

To this end we used a multiple associate learning paradigm (adapted from Weber et al., 2014): While learning word-pair associations, participants were challenged with three different secondary tasks (i.e., an internal, an external, and a control task). The internal secondary task (*internal condition*) asked participants to monitor their thought during the encoding of word pairs. The external secondary task (*external condition*) engaged participants in judging the similarity of subsequent auditory simple tones. In the high-level perceptual *control condition*, participants simply pressed a button for every occurrence of a tone (see Fig. 1). Memory performance was assessed with a covert cued-recall test.

Behavioral hypotheses

For our hypothesis, we focused on impaired memory performance for both internal and external secondary task conditions compared to the control condition. In line with previous research, we hypothesized that the external condition would impair memory performance by (i) competing for general processing resources (such as attention and working memory capacity) with the primary word-pair learning (Uncapher and Rugg, 2005), and by (ii) disrupting encoding processes (Kensinger et al., 2003; Uncapher and Rugg, 2008). Regarding the internal secondary task, we assumed that it affects executive resources and memory encoding similarly, albeit due to an inward focus of attention. This difference, although not necessarily evident in behavioral memory performance, should be visible in different underlying brain mechanisms supporting internal and external secondary task performance.

Neurophysiological hypotheses

For both the internal and external condition compared to the control condition, we expected activity decreases in brain regions involved in memory encoding (e.g. the hippocampus, cf. Kensinger et al., 2003; Uncapher and Rugg, 2008) and semantic processing of the to-be-remembered items (inferior frontal gyrus; cf. Shallice et al., 1994; Fletcher et al., 1995; Iidaka et al., 2000; Anderson et al., 2000). Moreover, as the internal secondary task requires shifting attention between internal thoughts and external stimulation, we expected additional brain systems to be involved compared to the external condition; candidate brain regions are detailed in the following paragraphs.

As described above, the internal secondary task triggers heightened cognitive self-consciousness, an inwardly-focused cognitive process that has not been investigated via brain imaging techniques so far. Therefore, in order to generate hypotheses concerning the underlying neural mechanisms, we refer to related constructs whose neural correlates are already better understood. Three concepts that share features with heightened cognitive self-consciousness are task-relevant interferences (Stawarczyk et al., 2011a; Stawarczyk et al., 2011b), performance monitoring (Ridderinkhof et al., 2004), and mind wandering (Gusnard and Raichle, 2001; Mason et al., 2007; Christoff et al., 2009). Starting with the latter, mind wandering has been defined as self-generated mental activity that is unrelated to external perceptual input (Smallwood, 2013) and, thus, shares the feature of inwardly focused attention with cognitive self-consciousness. From a neurophysiological perspective, mind wandering has been associated with activity in the *default mode network*, including the anterior medial prefrontal cortex (PFC), posterior cingulate cortex and precuneus, as well as the temporoparietal junction; activity in this network is typically observed in resting state (Gusnard and Raichle, 2001; Mason et al., 2007; Christoff et al., 2009). However, while mind wandering is commonly understood as being unconstrained and task-irrelevant (Smallwood, 2013), we argue that in healthy populations, heightened cognitive self-consciousness relates closer to the actual primary task: for example, sitting in a lecture and having difficulty staying attentive, you put effort to closely monitor your focus of attention. Following this line of argumentation, heightened cognitive self-consciousness is an inherently secondary task, as it is always concerned with an ongoing primary thinking process. In consequence, heightened cognitive self-consciousness comprises aspects of performance monitoring (i.e. the continuous monitoring of actions and the outcome of actions) (Ridderinkhof et al., 2004) and so-called task-relevant interferences (i.e., cognitive appraisals of the current task, such as e.g. task length or mistakes made earlier) (Stawarczyk et al., 2011b). The following paragraph will detail the neurophysiological hypotheses emerging from the conceptual relations between heightened cognitive self-consciousness, performance monitoring, and task-relevant interferences.

Heightened cognitive self-consciousness and *performance monitoring* share a scrutinizing focus on ongoing activity. To some extent, they both compare these actions to inner standards, even though heightened cognitive self-consciousness is not focused on overt behavior, but rather on the thinking process. Conditions requiring intensified performance monitoring, such as response conflict, response uncertainty, and response errors, result in increased activity in the anterior cingulate cortex (ACC) (Ridderinkhof et al., 2004; Kanske and Kotz, 2011) and in the anterior insula (Klein et al., 2007, 2013; Ullsperger et al., 2010). Both regions are discussed as core nodes of the salience (Menon and Uddin, 2010) or task control network (Dosenbach et al., 2007) and thus, also qualify as potential support regions for heightened cognitive self-

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