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Mental rotation impairs attention shifting and short-term memory encoding: Neurophysiological evidence against the response-selection bottleneck model of dual-task performance

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ABSTRACT

Dual tasks and their associated delays have often been used to examine the boundaries of processing in the brain. We used the dual-task procedure and recorded event-related potentials (ERPs) to investigate how mental rotation of a first stimulus (S1) influences the shifting of visual-spatial attention to a second stimulus (S2). Visual-spatial attention was monitored by using the N2pc component of the ERP. In addition, we examined the sustained posterior contralateral negativity (SPCN) believed to index the retention of information in visual short-term memory. We found modulations of both the N2pc and the SPCN, suggesting that engaging mechanisms of mental rotation impairs the deployment of visual-spatial attention and delays the passage of a representation of S2 into visual short-term memory. Both results suggest interactions between mental rotation and visual-spatial attention in capacity-limited processing mechanisms indicating that response selection is not pivotal in dual-task delays and all three processes are likely to share a common resource like executive control.

1. Introduction

Performing two tasks at the same time can overload the capacity of the brain in such a way that performance is delayed or impaired. And yet, some combinations of tasks seem to be easier to perform than others, suggesting that the costs of multitasking depend on the types of cognitive processes that overlap in time. A particularly helpful tool in telling apart processes that do and do not produce dual-task costs is the so-called psychological refractory period (PRP) paradigm (Telford, 1931). This paradigm commonly involves a dual task (Task 1 and Task 2) in which two stimuli (S1, S2) are presented, and each requires a speeded response (R1, R2). The two stimuli are separated in time by a stimulus onset asynchrony (SOA), so as to manipulate the temporal overlap of the two tasks. Results typically show an increased reaction time (RT) to S2 (RT2) with decreasing SOA, suggesting that some processes necessary to carry out the second response need to wait (or slow down) until some other processes in the first task have been completed-this slowing of R2 is called the PRP effect (Welford, 1967).

Under the assumption of a single capacity limitation, the combined effect on RT2 of SOA and a Task 2 variable can clarify which processes are deferred in the PRP paradigm. Capacity-limited processes of Task 1 and Task 2 cannot run simultaneously, while processes occurring before or after the capacity-limited process of one task can be performed concurrently with any other process of the other task (capacity limited or not). If the effect of a Task 2 variable onto RT2 is equal for short and long SOAs (i.e., additive with the SOA effect), this implies that the Task 2 effect is related to a capacity-limited Task 2 process or some other process following this capacity-limited process. If instead the effect of the Task 2 variable is smaller for short than for long SOAs (i.e., combines underadditively with the SOA effect, as SOA is reduced), this implies that at least some of the Task 2 effect arises before capacity-limited processes. Underadditive effects are thought to occur because at short SOAs capacity-limited processes are deferred, and this causes a state of slack for Task 2 processes. This slack in a sense “swallows” at least part of the Task 2 effect, so that a Task 2 variable that affects processes preceding the capacity limitation in Task 2 delays RT2 for a shorter time with short than with long SOAs (Pashler & Johnston, 1989). Additional clues about which processes are capacity limited

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can come from the effect of Task 1 variables onto RT2. Effects of Task 1 variables on capacity-limited processes or earlier will defer Task 2 processes and affect RT2, whereas Task 1 variables that take effect after capacity-limited processes will not affect RT2.

Several PRP studies employing the logic described in the above have yielded support for a response-selection bottleneck model (Pashler, 1994; Smith, 1967; Welford, 1952, 1980), which assumes that response selection – a process of translating stimulus codes to response codes (Pashler & Johnston, 1989) – is the major bottleneck in multitasking, in the sense that only one response can be selected at a time. Even though the response-selection bottleneck model has been very successful in explaining a wide variety of observations (see Pashler, 1994, for an overview), there is increasing evidence that response selection is not the only cognitive process with bottleneck characteristics. In the present study, we focused on two processes that based on previous observations can be suspected to have such characteristics: mental rotation and the shifting of visual-spatial attention. In contrast to previous studies that investigated the interaction between these processes and response selection, we were interested in the direct interaction between mental rotation and attentional shifting. Before we describe the rationale of our study in more detail, we first review the available evidence suggesting that mental rotation and attentional shifting might indeed possess bottleneck characteristics.

1.1. Mental rotation

In a mental-rotation task, participants categorize asymmetric visual stimuli, such as (most) letters, as normally oriented vs. mirror-reversed. Importantly, the stimuli are rotated to some angle from their usual upright orientation, which makes the task more difficult. Results show that RT increases monotonically with increasing angle from normal orientation (Cooper, 1975, 1976; Cooper & Shepard, 1973; Shepard & Metzler, 1971). Although the mechanisms underlying this observation are still largely unknown, the empirical findings are very robust and replicable (see Shepard & Cooper, 1982, for a review). As suggested by the study of Corballis (1986), the mirror/normal discrimination can only be made if participants have actually carried out something like a mental rotation of the stimulus representation into the normal upright position. This process is assumed to have analog characteristics, so that stimuli that deviate more strongly from their normal position have to be "mentally rotated" for a longer time-which is taken to explain the monotonic, and often linear, relationship between RT and rotation angle.

From a response-selection bottleneck model, one would not expect that mental rotation as indexed in such a comparison task shares resources with response selection. And yet, there is evidence suggesting this possibility. A number of studies have looked into the interactions between mental rotation and response selection in a PRP paradigm. With a mental-rotation task as Task 2, Ruthruff, Miller, and Lachmann (1995) observed that a large proportion of the Task 2 orientation effect was still present at very short SOAs and concluded that mental rotation shares limited capacity with response selection in Task 1. Comparable findings were reported by Van Selst and Jolicœur (1994), Heil, Wahl, and Herbst (1999), and others; and Band and Miller (1997) observed that mental rotation interferes with concurrent response preparation. Taken together, these studies provide strong evidence that mental rotation has bottleneck properties similar to response selection.

1.2. Visual-spatial attention shifting

Considering their different computational functions, the observed similarities between mental rotation and response selection may seem rather surprising. Probably less surprising are commonalities between deployment of visual attention (involving disengagement, shifting and engagement of visual attention) and response selection. The main function of a response-selection process should be the identification and activation of the cognitive representation of an action that meets the current situational requirements and task goals. Visual attention often serves comparable purposes by identifying and activating the cognitive representation of a relevant stimulus or target, and by optimizing the collection of information about this stimulus by directing attention to its location in space. Accordingly, if response selection draws on cognitive resources to a degree that renders it an effective processing bottleneck, it makes sense to assume that stimulus selection does the same. Investigations of the possible bottleneck characteristics of visual attention shifting turned out to be rather varied however.

A first study addressing this issue was reported by Pashler (1991), who investigated the potential bottleneck properties of visual-spatial attention in a dual task. In his PRP study, Task 1 was a tone identification task and Task 2 was an unspeeded masked-letter identification task. If spatial attention has bottleneck properties and spatial attention is required to perform Task 2, then accuracy on Task 2 should be impaired at short SOAs, that is, if response selection in Task 1 would temporally overlap, and slow or postpone, directing attention in Task 2. In view of a small interaction of Task 2 performance and SOA (although the effect was statistically significant), Pashler concluded that visual-spatial attention does not have bottleneck properties. But note that Dell'Acqua and Jolicœur (2000) arrived at a different conclusion when they used a more complex first task.

Along the same lines, Johnston, McCann, and Remington (1995) asked whether attention is one unitary process comprising of both input selection and output selection or rather a set of separate and dissociable selection processes by measuring both input selection and output selection in two separate experiments. Based on the results, Johnston et al. (1995) argued that input and output attention can be seen as a set of related but separate selection processes, in which response selection-conceived of as "central," capacity-limited process-prevents the simultaneous execution of other capacity-limited processes, whereas the deployment of visual-spatial attention can overlap other capacity-limited or unlimited processes. But note that this conclusion was drawn from a comparison across two separate experiments, without directly looking into the interaction between response selection and attentional shifting.

Even though these first studies did not seem to provide strong evidence for the idea that shifting visual attention might possess bottleneck properties, more recent studies that used event-related brain potentials (ERP) have changed the picture considerably. Brisson and Jolicœur (2007a, 2007b) showed how the N2pc component (a negative posterior contralateral component that peaks usually after 200–300 ms) can be used to monitor task relevant visual-spatial attentional processes on a moment-to-moment basis in the context of dual-task situations (Brisson & Jolicœur, 2007a, 2007b) and others showed how the N2pc can also reflect attentional suppression of nontargets (Woodman & Luck, 1999, 2003). The N2pc is defined as activity measured over the contralateral electrode positions compared to activity over the ipsilateral electrode positions in the range of the N2 in the regular ERP, relative to the visual hemifield of the target (Eimer, 1996; Luck & Hillyard, 1994; Woodman & Luck, 2003). A difference wave is created when ERPs over ipsilateral are subtracted from ERPs over contralateral electrode positions. These difference waves are referred to as event-related lateralizations (ERL; Wascher & Wauschkuhn, 1996). The N2pc is generally observed on the lateral posterior sides of the head, usually with a maximum amplitude at electrode-pair PO7/PO8. Other nearby electrode-pairs are sometimes also