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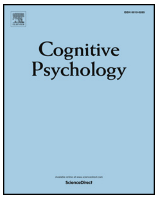

Set-shifting and place-keeping as separable control processes

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ABSTRACT

We present three experiments using a sequential binary choice task that explore the relationship between two proposed cognitive control functions: set-shifting and place-keeping (i.e., keeping track of one's place within a sequential task). The task involves switching from one stimulus-response mapping to another across trials, according to a predefined sequence and in the face of occasional brief interruptions. Response-stimulus interval, interruption length and interrupting task were varied. The robust finding across all experiments was that varying response-stimulus interval led to standard effects attributable to set-shifting, while varying interruption length led to standard effects attributable to place-keeping, but in no cases did the factors interact. We interpret the results as supporting the view that set-shifting and place-keeping are achieved by separable control processes and illustrate this interpretation with a computational model of performance on the task.

1. Introduction

Almost 25 years ago Rogers and Monsell (1995) lamented the fact that, while it had "long been understood that cognitive processes require control processes to organize them", the mechanisms supporting that control were "to put it mildly – poorly understood" (p. 207). Much progress has been made in the intervening years (see, Logie, 2016, for a recent summary and discussion), yet the majority of studies have focused on one aspect of cognitive control or "executive function" (whether it be related to set-shifting, response inhibition, etc.), typically using relatively simple tasks. There is of course good reason for this, as initial progress would not have been possible without good levels of process purity (i.e., tasks whose performance primarily involves the operation of a single putative executive function) and high levels of experimental control over the many variables that affect performance on tasks that require elements of cognitive control.

Yet many tasks, particularly those outside of the laboratory, involve multiple putative cognitive control mechanisms working together if appropriate (or even good) performance is to be achieved. Indeed, even the Wisconsin Card Sorting Task (WCST: Milner, 1963), which is widely used in the clinical assessment of executive functioning and where large numbers of perseverative errors are taken to indicate an impairment of such function, requires the coordinated operation of multiple processes to maintain a sorting rule in memory, process both positive and negative feedback, inhibit the use of failed sorting rules, and infer, select and apply alternative potential sorting rules. While the WCST is often considered to be a "set-shifting" task (i.e., a task that primarily taps the executive function of set-shifting: Miyake et al., 2000), the avoidance of perseverative errors actually requires the successful coordinated

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functioning of several different control processes (Stuss et al., 2000). Significant research questions therefore remain concerning the operation of control processes in more complex tasks.

This paper uses a task of moderate complexity to explore the operation and potential interaction of two processes that have been held to be involved in related aspects of cognitive control. The processes are set-shifting, for which there is a well-established literature spanning a century of work (see Monsell, 2003, and Vandierendonck, Liefooghe, & Verbruggen, 2010, for reviews and, in the latter case, a theoretical synthesis), and place-keeping, a control process introduced more recently by Altmann, Trafton, and Hambrick (2014) in order to account for participant performance on sequential tasks in the face of interruptions. We begin by reviewing the two processes before introducing a variant of Altmann et al.'s (2014) UNRAVEL task. We argue that performance of the task recruits both set-shifting and place-keeping processes, and present three experiments which suggest that these processes operate independently. On the basis of these results, we further argue that distinct representations of task are involved in the cognitive processes underlying set-shifting and place-keeping, and illustrate this with a computational model that simulates key behavioral effects.

1.1. *Set-shifting*

"Task set" refers to the configuration of the cognitive system required to perform a specific task (see, e.g., Logan & Gordon, 2001; Schneider & Logan, 2007), including the configuration of attentional and response-selection processes, the priming or activation of learned stimulus-response associations, and so on. Thus a color-naming task set would consist of attentional orientation to color input, activating associations between visual color inputs as stimuli and the corresponding verbal names as responses, and setting a suitable response-selection threshold for verbal output, while a word-reading task set would consist of attentional orientation to visual word inputs, activation of associations between visual word inputs as stimuli and the corresponding verbalizations as responses, and perhaps a similar response-selection configuration. Set-shifting is held to be required whenever higher order processing requires changing from one task set to another (i.e., whenever task-switching is required).

While a number of empirical paradigms have been developed to explore set-shifting, it is typically evidenced by choice reaction time tasks where participants respond by categorizing blocks of stimuli in different ways on different trials. Participants take longer to respond, and are more likely to err, on trials following a change in the categorization rule compared to trials that do not require a change in the rule – the so-called switch cost. There is debate about the cognitive processes that give rise to this cost. One view is that switch costs reflect management of interference from the preceding task set on the new task set (e.g., Allport & Wylie, 2000). A competing view is that they reflect processes involved in reconfiguring the cognitive system for the new task set (e.g., Rogers & Monsell, 1995). A middle ground is advocated by Vandierendonck et al. (2010), who argue that set-shifting requires both interference management and task set reconfiguration.

One key finding in the task-switching literature is that switch costs can be reduced by forewarning participants of an impending change of set. Thus, Rogers and Monsell (1995) used a set-shifting task in which participants could anticipate the task set that would be appropriate for the forthcoming stimulus. They explored the switch cost as a function of Response-Stimulus Interval (RSI: i.e., the interval between the response on trial $n - 1$ and the presentation of the stimulus on trial n). Switch costs were lower when the RSI was high compared to when it was low, suggesting that participants were able to use the RSI to prepare for the forthcoming task. However, the reduction in the switch cost was less than the increase in RSI (e.g., increasing RSI by 150 msec from 150 msec to 300 msec led to a reduction in switch cost of approximately 40 msec; Rogers & Monsell, 1995, experiment 4), and a residual switch cost remained even with very long RSI (1200 msec). One interpretation of this result is that when a task switch is predictable, participants may use the RSI to reconfigure the cognitive system in preparation for the upcoming task set, but that stimulus presentation is necessary to complete these reconfiguration processes (e.g., Rogers & Monsell, 1995; Meiran, 1996). Alternatively, the RSI may allow dissipation or inhibition of the activation of the previous (competing) task set, with stimulus presentation being necessary to optimize performance and minimize interference from activation of other task sets (e.g., Allport & Wylie, 2000). A third interpretation proposed by De Jong (2000) is that participants are indeed fully able to reconfigure their cognitive systems during a sufficiently long RSI, but that they do not do this on all trials. On some trials they may "fail-to-engage" in preparation. On this account the residual switch cost is an artefact of averaging RT over trials. De Jong (2000) supports this interpretation through an analysis of RT distributions.

Regardless of the precise origin of the residual switch cost, or of switch costs more generally, it is important to note for current purposes that the established view is that the processes required for task-set reconfiguration, i.e., processes related to the inhibition or disengagement of the current task set and/or the priming/engagement of the subsequent task set, must occur whenever switching from one task-set to another. That is, set-shifting is not a process that only occurs in studies that explicitly measure switch costs. It is a process, or collection of processes, that occur whenever a change of task set is required, as, for example, when it is necessary to respond to different aspects of a stimulus on successive trials.

1.2. *Place-keeping*

Studies of set-shifting typically require participants to switch between two or sometimes three tasks, with the target task on any trial being cued either explicitly or implicitly by some aspect of the stimulus, such as its position on the screen. Yet many tasks, particularly real-world tasks, are temporally extended and sequential in nature – they consist of multiple steps that should be performed in order but without explicit order cues. A fundamental question therefore concerns how the cognitive system generates sequential behavior. Prior to the cognitive revolution it had been argued that such behavior was the result of stimulus-response S-R chains (e.g., Washburn, 1916; Watson, 1920; cited in Lashley, 1951), with one response in a sequence serving as the stimulus for the

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