

Chunking away task-switch costs: a test of the chunk-point hypothesis

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Abstract Previous research has revealed that task-switch costs (worse performance for task switches than for task repetitions) at the first position of an explicit task sequence are eliminated or reduced when repeating or switching sequences. The authors hypothesize that such effects are restricted to points in the sequence representation that are associated with sequence-level processing such as chunk retrieval that changes the contents of working memory. In an experiment testing this chunk-point hypothesis, subjects memorized and performed explicit task sequences under different chunking instructions that induced chunk points at different positions within the sequences. Regardless of position, performance was slower at chunk points than at non-chunk points, providing direct evidence of chunking, and task-switch costs were reduced or eliminated at chunk points while they remained large and robust at non-chunk points. These findings support the chunk-point hypothesis and are discussed in relation to task-set inhibition and associative interference.

Keywords Chunking · Task sequences · Task switching · Working memory

Introduction

Task switching in everyday life sometimes occurs in the context of an explicit task sequence, as when a person uses a recipe for cooking a meal or follows instructions for assembling furniture. Task switching in the laboratory (for reviews,

see Kiesel et al., 2010; Vandierendonck, Liefoghe, & Verbruggen, 2010) also sometimes occurs in the context of an explicit task sequence, with mounting evidence that the structure of the sequence can affect task-switching performance (Koch, Philipp, & Gade, 2006; Lien & Ruthruff, 2004; Logan, 2004, 2007; Mayr, 2009; Schneider, 2007; Schneider & Logan, 2006, 2007). More specifically, performance may be affected by sequence-level processing associated with instantiating or maintaining an explicit task sequence in working memory, not just task-level processing associated with performing task computations on stimuli. For example, Lien and Ruthruff (2004) and Schneider and Logan (2006) found that task-switch costs (worse performance for task switches than for task repetitions) at the first position of a sequence are eliminated or reduced when repeating or switching sequences. Their results represent evidence that task transitions occurring in the context of an explicit task sequence are affected by sequence-level processing.

An open issue concerns the nature of the sequence-level processing that perturbs task-switching performance. Drawing upon theorizing about serial memory (Anderson, Bothell, Lebiere, & Matessa, 1998), we hypothesize that a major component of sequence-level processing is the retrieval of chunks of sequence information in the form of lists of task names or goals representing parts of a sequence (Logan, 2004, 2007; Schneider, 2007; Schneider & Logan, 2006). That is, when starting a sequence, sequence-level processing may involve retrieving a chunk representing an ordered list of task names, thereby making information about upcoming tasks accessible in working memory. There might be additional sequence-level processing associated with stepping through the list to perform the sequence (Anderson et al., 1998), but we think chunk retrieval is critical because it changes the contents of working memory.

Schneider and Logan (2006) suggested that this aspect of chunk retrieval may be responsible for the modulation of task-

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switch costs when repeating or switching sequences. If task-switch costs arise in part from differential activation of competing task sets in working memory (e.g., Yeung & Monsell, 2003), then changing the contents of working memory by retrieving a chunk may perturb task-set activation and, as a consequence, reduce task-switch costs by making task repetitions as difficult as task switches. However, once a chunk has been loaded into working memory, subsequent sequence-level processing within the chunk may involve only accessing—not changing—the sequence information in working memory. As a result, differences in task-set activation that arise during the performance of a sequence would remain unaffected, leading to typical task-switch costs within the sequence. Indeed, that is what has been found: task-switch costs are eliminated or reduced at the first position of a sequence, where chunk retrieval should occur, but they are large and robust at subsequent positions, where the relevant chunk is already in working memory (Schneider & Logan, 2006).

If chunk retrieval is the critical sequence-level process underlying perturbed task-switching performance, then task-switch costs should be reduced only at chunk points—those points in the sequence representation associated with retrieval of a chunk into working memory. Accordingly, the first position of every chunk in a sequence should be a chunk point (Anderson et al., 1998). The purpose of the present study was to test the idea that task-switching performance is perturbed only at chunk points, which we refer to as the chunk-point hypothesis.

A short sequence of three or four tasks is likely to be represented as a single chunk, with the first position of the sequence being the chunk point. Based on the chunk-point hypothesis, one would predict task-switch costs to be reduced at the first position but not at subsequent positions, which is what Schneider and Logan (2006) found. In contrast, a long sequence of tasks, especially one that approaches or exceeds working memory capacity (e.g., six or more tasks), is likely to be represented as multiple chunks (Logan, 2004; Miller, 1956). To ease the burden on working memory, information from only a single chunk might be loaded into working memory at a time (Schneider, 2007), and, once all the tasks in the chunk have been performed, the next chunk is retrieved (Anderson et al., 1998). Thus, there are multiple chunk points in the sequence, with their positioning determined by how the sequence is chunked. Based on the chunk-point hypothesis, one would predict task-switch costs to be reduced at every chunk point but spared at non-chunk points in a long sequence.

Although there have been task-switching studies involving explicit task sequences, none were designed to investigate how chunking affects task-switch costs. Koch et al. (2006), Schneider (2007), and Mayr (2009) investigated chunking of explicit task sequences in relation to a task-switching effect attributed to task-set inhibition (Mayr & Keele, 2000), but they did not include immediate task repetitions to enable assessment of task-switch costs. Logan (2004) examined

chunking in his study of task span (the number of tasks that can be maintained in working memory and performed accurately), but most of his experiments were designed such that task repetitions could occur at chunk points but not within chunks. Schneider and Logan (2006) studied task-switch costs in explicitly memorized six-task sequences, but they found little evidence suggesting that their sequences were chunked. In summary, past research cannot be used to test the predictions of the chunk-point hypothesis for long, explicitly memorized task sequences.

We evaluated the chunk-point hypothesis with an experiment in which we manipulated the chunking of explicit task sequences to perturb task-switching performance at different positions within the sequences. Two groups of subjects memorized and repeatedly performed (in separate halves of the experiment) two six-task sequences of the forms ABAABB and BABAAB (where A and B denote different tasks) under different instructions for chunking the sequences. One group was instructed to memorize each sequence by chunking it into sets of three tasks (3–3 chunking instructions; e.g., ABA–ABB and BAB–AAB, where “–” represents a chunk boundary). The other group was instructed to memorize each sequence by chunking it into sets of four and two tasks (4–2 chunking instructions; e.g., ABAA–BB and BABA–AB). If the positions in each sequence are labeled 1–6 from left to right, then Position 1 is a chunk point for both instructional groups, Position 4 is a chunk point for the 3–3 group but not for the 4–2 group, and Position 5 is a chunk point for the 4–2 group but not for the 3–3 group. Based on the chunk-point hypothesis, we predict that task-switch costs will be reduced at positions that are chunk points, but large and robust at positions that are non-chunk points. Critically, these predictions should hold even for Positions 4 and 5, each of which is a chunk point for one instructional group but not for the other. Besides investigating task-switch effects, we will also examine whether response congruency effects are perturbed at chunk points. Response congruency refers to whether a stimulus requires the same response (congruent) or different responses (incongruent) across tasks, with the typical finding of worse performance for incongruent trials than for congruent trials (Kiesel, Wendt, & Peters, 2007; Meiran & Kessler, 2008; Schneider, 2014). If response congruency effects are susceptible to the same kind of disruption as task-switch effects at chunk points, then it would suggest that sequence-level processing can influence response selection at the task level.

Method

Subjects

Thirty-two students from Vanderbilt University completed the experiment for course credit or US\$12. Sixteen students were

assigned to each instructional group (receiving either 3–3 or 4–2 chunking instructions).

Design and materials

The tasks were origin (living or nonliving) and size (small or large, relative to a basketball) judgments on the referents of word stimuli. The stimuli were 64 words used previously by Schneider and Logan (2007), with 16 words for each category combination. All stimuli were displayed on a computer monitor in white 12-point Courier New font on a black background and viewed at a distance of about 60 cm.

The tasks were performed according to two explicit task sequences, with each sequence relevant for half of the experiment. The sequences were of the forms ABAABB and BABAAB, where A and B denote different tasks. Sequence order and the designation of the origin and size tasks as A and B were counterbalanced across subjects. The sequences were chosen for their similar complexity and because each sequence can be phase-shifted to produce the other.

The sequences were performed according to instructions for chunking them (following Schneider, 2007). Different groups of subjects were instructed to memorize each sequence by chunking it into either sets of three tasks (3–3 chunking instructions) or sets of four and two tasks (4–2 chunking instructions). Each sequence was displayed onscreen during the instructions as a series of task names (e.g., *ORIGIN, SIZE, ORIGIN, SIZE, SIZE, ORIGIN*) with a larger gap between the third and fourth names (3–3 chunking instructions) or the fourth and fifth names (4–2 chunking instructions) to illustrate how the sequences should be chunked.

Procedure

Subjects were seated in front of computers in individual testing rooms after providing informed consent for a study protocol approved by the Vanderbilt University Institutional Review Board. Instructions were presented onscreen and explained by the experimenter. The experiment was divided into two halves. At the start of each half, subjects were presented with a sequence to memorize for subsequent performance. After memorization under the relevant chunking instructions, the sequence was performed iteratively for 11 blocks of 42 trials, with the first block and the first iteration per block considered practice.

On each trial, a word stimulus appeared in the center of the screen and a task was performed on it by pressing the Z or / key on a QWERTY keyboard. Same-task categories were assigned to different keys and all possible category–response mappings were counterbalanced across subjects. As there were no external task cues, subjects had to rely on their memory of the sequence and the current position in the sequence to determine the task on each trial, repeating the

sequence every six trials. After a response, the screen was cleared (no feedback was provided) and the next trial commenced after 500 ms.

Results

Blocks with error rates exceeding 20 % (2.3 % of blocks) and trials with response times (RTs) exceeding 5,000 ms (1.0 % of trials) were excluded. A block error-rate criterion was implemented to account for rare instances when subjects lost track of where they were in the sequence during a block. Error trials were excluded from the RT analysis. Mean RTs and error rates are provided as a function of chunking instructions, sequence, and position in Table 1. The data from Positions 1, 4, 5, and 6 (each of which involves both task transitions across sequences) were used to calculate mean RTs and error rates as a function of chunking instructions (3–3 or 4–2), chunk-point status (chunk point or non-chunk point), task transition (task switch or task repetition), and response congruency (incongruent or congruent), which were submitted to mixed-measures analyses of variance (ANOVAs) with chunking instructions as a between-subjects factor and the remaining variables as within-subjects factors. The ANOVA results are summarized in Table 2 and referenced in the following text.

Figure 1 shows mean RTs and error rates as a function of chunk-point status and task transition. The data were averaged over chunking instructions because that factor was not involved in any interactions and yielded only a significant main effect on RT, reflecting shorter RT for the 3–3 group (1,071 ms) than for the 4–2 group (1,255 ms). RT was longer at chunk points (1,316 ms) than at non-chunk points (1,010 ms), resulting in a significant main effect of chunk-point status and representing characteristic evidence of chunking (e.g., Povel & Collard, 1982; Rosenbaum, Kenny, & Derr, 1983; Schneider, 2007). Task switches (1,202 ms)

Table 1 Mean response times (in milliseconds) and mean error rates (percentages in parentheses) as a function of chunking instructions, sequence, and position

Chunking instructions	Sequence	Position					
		1	2	3	4	5	6
3–3	ABAABB	1,241 (4.0)	1,200 (4.4)	1,123 (2.8)	1,138 (1.8)	963 (4.3)	793 (2.1)
	BABAAB	1,367 (1.9)	1,160 (5.3)	1,204 (4.8)	1,181 (2.1)	824 (1.6)	1,052 (2.8)
4–2	ABAABB	1,417 (2.7)	1,339 (2.5)	1,328 (3.0)	943 (2.9)	1,226 (3.4)	965 (1.6)
	BABAAB	1,572 (3.4)	1,251 (3.3)	1,325 (3.0)	1,262 (5.4)	1,380 (3.3)	1,270 (3.5)

Table 2 Summary of the ANOVA results

Effect	Response time			Error rate		
	<i>F</i> (1,30)	<i>MSE</i>	η_p^2	<i>F</i> (1,30)	<i>MSE</i>	η_p^2
Chunking instructions (I)	6.09*	354,075	.17	1.53	16.57	.05
Chunk-point status (C)	89.19*	66,957	.75	0.24	6.81	.01
Task transition (T)	21.10*	18,001	.41	19.09*	4.88	.39
Response congruency (R)	11.73*	10,882	.28	57.14*	9.49	.66
I × C	0.35	66,957	.01	<0.01	6.81	<.01
I × T	0.03	18,001	<.01	0.45	4.88	.02
I × R	0.25	10,882	.01	0.58	9.49	.02
C × T	38.17*	52,940	.56	2.59	12.62	.08
C × R	<0.01	6,736	<.01	7.59*	5.87	.20
T × R	2.47	9,776	.08	5.06*	3.85	.14
I × C × T	3.77	52,940	.11	1.21	12.62	.04
I × C × R	1.16	6,736	.04	2.10	5.87	.07
I × T × R	0.17	9,776	.01	0.13	3.85	<.01
C × T × R	0.66	4,570	.02	5.60*	8.94	.16
I × C × T × R	<0.01	4,570	<.01	1.78	8.94	.06

**p* < .05

were slower than task repetitions (1,125 ms), resulting in a significant main effect of task transition. However, this effect was qualified by a significant interaction between chunk-point status and task transition. As shown in Fig. 1, there was a large task-switch cost at non-chunk points but a numerical task-switch benefit at chunk points, consistent with the predictions of the chunk-point hypothesis. The analogous effects were weaker in the error data, where there was a large task-switch cost at non-chunk points and a much smaller cost at chunk

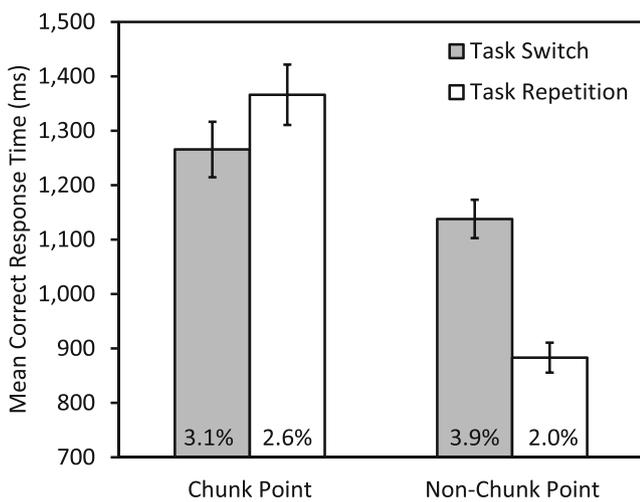


Fig. 1 Mean correct response time (bars) and mean error rate (percentages shown in bars) as a function of chunk-point status (chunk point or non-chunk point) and task transition (task switch or task repetition). Error bars standard errors of the means

points, although the interaction between chunk-point status and task transition was nonsignificant (*p* = .12).

The preceding analyses were repeated on data only from Positions 4 and 5, each of which was a chunk point for one instructional group but not for the other, providing a stronger test of the chunk-point hypothesis. Figure 2 shows mean task-switch effects on RT and error rate as a function of chunking instructions and position. The critical effects on RT remained significant. RT was longer when a position was a chunk point (1,233 ms) than when it was a non-chunk point (1,000 ms), resulting in a significant main effect of chunk-point status, *F*(1,30) = 42.34, *MSE* = 81,826, *p* < .05, η_p^2 = .59, and providing evidence of chunking beyond the first position of each sequence. The interaction between chunk-point status and task transition remained significant for RT, *F*(1,30) = 12.81, *MSE* = 104,454, *p* < .05, η_p^2 = .30, and was nearly significant for error rate, *F*(1,30) = 3.93, *MSE* = 21.21, *p* = .057, η_p^2 = .12. As shown in Fig. 2, there was a large task-switch cost for RT when a position was a non-chunk point and either a negligible task-switch cost or a task-switch benefit when a position was a chunk point, consistent with the predictions of the chunk-point hypothesis. An analogous pattern was obtained in the error data, where there were large task-switch costs at non-chunk points and negligible costs at chunk points.

Robust response congruency effects were observed, with slower and more error-prone performance on incongruent trials (1,186 ms for RT; 4.4 % for error rate) than on congruent trials (1,141 ms; 1.4 %), resulting in significant main effects of response congruency on RT and error rate. Response congruency did not interact with any other factor in the RT data; notably, the response congruency effect was 45 ms at chunk and non-chunk points. However, response congruency was

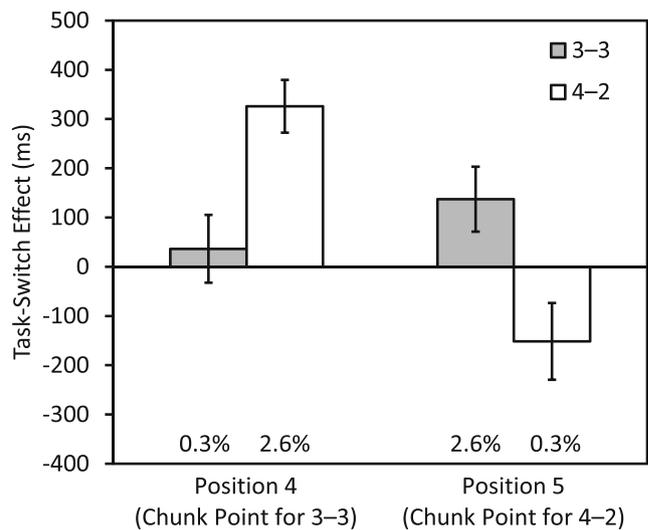


Fig. 2 Mean task-switch effects (positive values are task-switch costs) for response time (bars) and error rate (percentages shown below bars) as a function of chunking instructions (3–3 or 4–2) and position (4 or 5). Error bars standard errors of the means

involved in multiple interactions in the error data, culminating in a three-way interaction with chunk-point status and task transition. The interaction reflects a larger response congruency effect for task switches (5.2 %) than for task repetitions (2.3 %) at non-chunk points, but a numerical reversal of the difference at chunk points (1.7 and 2.4 % for task switches and task repetitions, respectively). Given the inconsistency of interactions between response congruency and task transition (see Schneider, 2014), we think the key result is that response congruency effects were found at both chunk and non-chunk points, in contrast with the pattern for task-switch effects.

Discussion

The purpose of the present study was to investigate the nature of the sequence-level processing that affects task-switching performance in explicit, memorized task sequences. Based on previous research (Anderson et al., 1998; Schneider & Logan, 2006), we suggested that retrieving a chunk of sequence information changes the contents of working memory and perturbs the differential task-set activation that may underlie task-switch costs. This led us to propose the chunk-point hypothesis, which is the idea that task-switch costs in the performance of explicit task sequences should be reduced at chunk points—positions involving sequence-level processing associated with chunk retrieval. In an experiment testing this hypothesis, we instructed subjects to chunk sequences in different ways, resulting in chunk points at some positions but not at others. Performance was slower at chunk points than at non-chunk points, providing direct evidence that subjects chunked the sequences as instructed. Critically, task-switch costs were reduced or eliminated at chunk points while they remained large and robust at non-chunk points, even when the first position of each sequence was excluded from analysis. The sequence-level processing that disrupted task-switching performance had muted consequences for response congruency effects, which were present at both chunk and non-chunk points, suggesting that response selection at the task level was relatively unaffected. In the remainder of this article, we discuss two possible explanations for why task-switch costs are not just reduced at chunk points, but sometimes become benefits, as observed in our RT data (see Fig. 1) and in past studies (Lien & Ruthruff, 2004; Schneider & Logan, 2006).

Task-set inhibition

One explanation is that task-switch benefits arise from task-set inhibition (Mayr & Keele, 2000; for a review, see Koch, Gade, Schuch, & Philipp, 2010). When switching among three tasks (A, B, and C), performance is worse for lag-2 task repetitions (e.g., ABA) compared with lag-2 task switches (e.g., CBA). The prevailing explanation of this lag-2 task-repetition cost is

task-set inhibition: Switching from Task A to Task B in an ABA sequence involves inhibition of the task set for Task A. Switching back from Task B to Task A requires extra time to overcome this inhibition, leading to longer RTs for lag-2 task repetitions. When switching from Task B to Task A in a CBA sequence, inhibition of the task set for Task A has occurred less recently, so there is less inhibition to overcome, leading to relatively shorter RTs for lag-2 task switches. The result is a lag-2 task-repetition cost.

We have assumed there are only two tasks in the present study (origin and size judgments). However, one might go beyond the experimentally defined tasks and think of chunk retrieval as a task unto itself (Schneider & Logan, 2014). From this perspective, two tasks are performed at each chunk point: chunk retrieval (which we will denote as Task C) and then an origin or size judgment (Task A or B). If switching to and from chunk retrieval is much like switching between other tasks, then a so-called task repetition occurring between chunks (e.g., ABA-ABB) becomes a lag-2 task repetition (ABA-CABB) and a so-called task switch occurring between chunks (e.g., BAB-AAB) becomes a lag-2 task switch (BAB-CAAB). If task-set inhibition occurs when retrieving a chunk, then one would expect a lag-2 task-repetition cost. In the present study, this effect would be manifest as a task-switch benefit, as observed at chunk points in the RT data (see Fig. 1). Thus, if one assumes that chunk retrieval is a third task in the experiment, then task-switch benefits can be explained by task-set inhibition.

Associative interference

An alternative explanation is that task-switch benefits arise from associative interference. We have assumed that once a chunk has been loaded into working memory, it is protected in the sense that there will not be an attempt to retrieve a new chunk until such retrieval is necessary (Anderson et al., 1998). However, given that the same tasks appear in different chunks (e.g., Task A appears in both chunks of an ABA-ABB sequence under 3–3 chunking instructions), it is possible that task-related representations (e.g., task names or goals) will retrieve chunks with which they are associated, generating interference (see Mayr, 2009, for evidence of interference in chunked task sequences). For a task repetition between chunks (e.g., ABA-ABB), maintenance of the newly loaded ABB chunk in working memory may be affected by the first task in the chunk (Task A) having just occurred in the context of the ABA chunk. Even though the ABA chunk is no longer relevant, the immediate recurrence of Task A may promote retrieval of that chunk, interfering with maintenance of the ABB chunk. Moreover, the fact that both chunks in this example (ABA and ABB) start with Task A may generate confusion about which chunk is currently relevant. For a task switch between chunks (e.g., BAB-AAB), such associative

interference may be less likely to occur because the first task of the new chunk differs from the last task of the previous chunk. In addition, both chunks in this example (BAB and AAB) start with different tasks, limiting confusion about which chunk is currently relevant. If associative interference is largely restricted to task repetitions between chunks, as in the preceding examples, then task-switch benefits could arise.

This kind of associative interference suggests an interactive relationship between the sequence and task levels in working memory. On the one hand, sequence-level processing determines which task-related representations gain access to working memory, perturbing task-set activation carried over from recent trials in a way that reduces task-switch costs at chunk points. On the other hand, task-level processing may induce the retrieval or updating of associated sequence-related representations in working memory, interfering with chunk implementation in a way that disproportionately affects task repetitions, sometimes resulting in task-switch benefits. By integrating models of serial memory (e.g., Anderson et al., 1998) with models of task switching (e.g., Schneider & Logan, 2005) in future work, it may be possible to explore this interactive relationship and achieve a better understanding of how associative interference might be generated between the sequence and task levels in working memory during the performance of explicit, memorized task sequences.

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