Research Article

Chunking in Task Sequences Modulates Task Inhibition

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ABSTRACT—*In a study of the formation of representations of task sequences and its influence on task inhibition, participants first performed tasks in a predictable sequence (e.g., ABACBC) and then performed the tasks in a random sequence. Half of the participants were explicitly instructed about the predictable sequence, whereas the other participants did not receive these instructions. Task-sequence learning was inferred from shorter reaction times (RTs) in predictable relative to random sequences. Persisting inhibition of competing tasks was indicated by increased RTs in n − 2 task repetitions (e.g., ABA) compared with n − 2 nonrepetitions (e.g., CBA). The results show task-sequence learning for both groups. However, task inhibition was reduced in predictable relative to random sequences among instructed-learning participants who formed an explicit representation of the task sequence, whereas sequence learning and task inhibition were independent in the noninstructed group. We hypothesize that the explicit instructions led to chunking of the task sequence, and that n − 2 repetitions served as chunk points (ABA-CBC), so that within-chunk facilitation modulated the inhibition effect.*

The mechanisms underlying executive control of task performance can be explored using the task-switching paradigm (see Monsell, 2003, for a review). The rationale of this paradigm is that a multitask situation requires flexible adaptation of the cognitive system to changing task demands, whereas this adaptation would not be required (or at least would not be measurable) when studying performance in a constant task. However, although studies using the task-switching paradigm focus on the cognitive mechanisms that configure the system for the upcoming task in a multitask context, the level of analysis is still the performance of an individual task.

In fact, the proposed mechanisms for the executive control of tasks are thought to reduce the potentially interfering influence of competing tasks. For example, models assuming reconfiguration of cognitive task representations (i.e., task sets) typically assume that the cognitive system can be configured for one or another task, but not for several tasks at the same time (Monsell, 2003). Moreover, it has been suggested that there is a special inhibitory mechanism that "deletes" a potentially competing task from working memory, so that it does not interfere with the currently relevant task (e.g., Mayr & Keele, 2000). As a consequence, although task-switching studies analyze sequential effects in task performance, the theoretical focus is on the performance of individual tasks, not on task sequences.

The aim of the present study was to explore the mechanisms that control the performance of task sequences. These mechanisms go beyond those postulated in traditional models of task switching. We assume that there are mechanisms that enable the formation of higher-order representations of task sequences, just as it has been postulated that higher-order motor representations underlie action sequences (see Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003, for a review).

The existence of higher-order representations of task sequences was recently proposed by Luria and Meiran (2003). They postulated that in situations with temporally overlapping tasks (i.e., dual tasks), task order is explicitly represented in the form of an "order set." Likewise, Lien and Ruthruff (2004) suggested that typical task-switching studies induce a "flat task structure," and they demonstrated that hierarchical structures can also be induced, leading to higher-order representations of "task ensembles." Finally, Logan (2004) recently explored participants' memory span for task sequences that they are instructed about explicitly. The goal of the present study was to examine the formation of higher-order task representations using a sequence-learning paradigm.

Gotler, Meiran, and Tzelgov (2003) recently used a sequence-learning paradigm to compare performance in a predictable eight-trial sequence of two different tasks with performance in random sequences of the tasks. They found a performance benefit for predictable task sequences. However, this study

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focused mainly on demonstrating implicit learning and whether it affects the performance cost of switching compared with repeating a task (see also Heuer, Schmidtke, & Kleinsorge, 2001; Koch, 2001). In contrast, the present study focused on the mechanism underlying the learning process and whether it affects inhibitory processes in task switches.

Learning a task sequence requires forming associations between tasks, so that the upcoming task can be anticipated on the basis of the current task. This implies forming a representation of a task sequence (Keele et al., 2003). The literature on implicit learning (see Dienes & Berry, 1997, for a review) suggests that such associations can span up to three or four sequence elements (e.g., Cleeremans & McClelland, 1991). In particular, the formation of hierarchical representations is usually attributed to a *chunking* process, which is often accompanied by explicit sequence knowledge (cf. Curran, Smith, DiFranco, & Daggy, 2001). It is important to note that chunks can be formed spontaneously, but there are factors, such as spatial or temporal grouping, that can induce chunks (e.g., Koch & Hoffmann, 2000; Lien & Ruthruff, 2004). Another factor favoring the formation of chunks is the presence of structured relations among sequence elements (Koch & Hoffmann, 2000), such as alternations (e.g., Restle, 1970), referred to as $n - 2$ repetitions. The present study examined learning of a task sequence that contained frequent $n - 2$ repetitions (e.g., ABA).

In task switching, it has been shown that $n - 2$ task repetitions are associated with a performance cost relative to nonrepetitions (e.g., CBA). This cost has been attributed to a control mechanism that inhibits the previous task set when a new task is performed, so that persisting inhibition slows down performance of the just-abandoned task when it becomes relevant again (Mayr & Keele, 2000; see also Houghton & Tipper, 1996). The present study examined whether task-sequence learning affects this task inhibition.

Specifically, we presented task sequences containing two $n - 2$ repetitions (e.g., ABACBC) and contrasted performance in these predictable sequences with that in (pseudo-) random sequences. The random sequences preserved the frequency of individual tasks and task pairs, so that empirically observed learning effects were necessarily due to learning of at least triplets of tasks (cf. Reed & Johnson, 1994).

If $n - 2$ repetitions are preferred "chunk points," it is possible that learning, for example, the sequence ABACBC leads to a representation of the form ABA-CBC, so that each $n - 2$ task repetition is embedded in a chunk. Because performance of tasks within a chunk—and, in particular, performance of $n - 2$ repetitions within a chunk—should be facilitated, this hypothesized chunking process should decrease task inhibition (i.e., the $n - 2$ repetition cost) as a function of task-sequence learning.

However, because previous studies have suggested that task-sequence learning is accompanied by very low levels of sequence awareness (e.g., Gotler et al., 2003; Koch, 2001), and

because we speculated that the spontaneous formation of effective chunks requires explicit sequence knowledge, we tested two groups of participants given different task instructions. To induce (or prime) the chunking process, we explicitly informed one group of participants about the repeating, predictable task sequence and explained the order of the tasks (instructed-learning group). In contrast, the other group's instructions did not include any reference to a possible task sequence (incidental-learning group). We reasoned that revealing the sequence would render the $n - 2$ repetition among the tasks more noticeable, so that the formation of corresponding chunks would be more likely in the instructed-learning group than in the incidental-learning group, even though it would be possible in the incidental-learning group, too. On the basis of this reasoning, we hypothesized that the learning process would affect our measure of task inhibition more in the instructed- than in the incidental-learning group.

An influence of task-sequence learning on task inhibition would be a novel phenomenon. Task preparation on the level of isolated tasks (i.e., based on an explicit task cue prior to the imperative stimulus) has been shown to be ineffective in influencing task inhibition (e.g., Mayr & Keele, 2000; Schuch & Koch, 2003), so that finding such an influence based on learned sequential representations would be theoretically important. In particular, it would suggest that there are higher-order control mechanisms relating to task sequences, and that these mechanisms can modulate the effect of control mechanisms on the level of individual tasks.

METHOD

Subjects

Eighty participants (57 female, 23 male; mean age = 25) were tested and were paid €7. The data of 7 participants were replaced because of high error rates (above 15%) or responses that were too slow (more than 10% outliers).

Tasks and Materials

The digit *4* and the letter *A* served as stimuli, presented one at a time on a 15-in. monitor. Each was displayed inside a white rectangle (4.0 cm high and 3.5 cm wide) on a black background. On a given trial, the stimulus could be either blue or red and either small (0.5 cm high) or large (1.0 cm high), resulting in eight different stimuli. The task cue for each trial was displayed at each of the four sides of the rectangle: A dollar sign (1.0 cm high) signaled that participants should report the form (F) of the stimulus, an arrow pointing upward and downward (0.8 cm high) signaled that they should report its size (S), and a yellow square (0.5 cm) indicated that they should report its color (C). Viewing distance was about 50 cm. For all tasks, responses were made on an external keyboard by pressing horizontally aligned keys with the index fingers of the left and right hands. The two response

keys measured approximately 1.7 cm and were spatially separated by 3.2 cm. Testing took place in a dimly lit, soundproof cubicle.

Procedure

The training sequence used was counterbalanced across participants: FSFCSC or CFCSFS. This sequence was repeated 12 times per block in Blocks 1 through 5, 7, 8, and 10. In Blocks 6 and 9, a pseudorandom sequence was presented, without warning. Task and transition frequencies of the pseudorandom sequence were matched to the training sequence. Stimulus and response sequences were always random, with the constraint that the eight stimuli appeared equally often in each block. The stimulus sequence was uncorrelated with the task sequence (cf. Koch, 2001).

The cue and stimulus-response (S-R) mapping for each task were explained. S-R mappings were counterbalanced across participants. A trial started with a blank screen for 100 ms. Then, the rectangle frame appeared, together with the task cue. After 100 ms, the stimulus appeared inside the frame, remaining until the participant responded, which initiated the next trial. In case of an error, the German word "Fehler" ("error") appeared at the bottom of the monitor. After each block of trials, participants received feedback about their mean reaction time (RT) in that block. The next block was self-initiated by any key press.

Half of the participants (instructed-learning group) were explicitly informed of the sequence in Blocks 1 through 5, 7, 8 and 10, and of the random sequence in Blocks 6 and 9. For these participants, the structure of the structured sequence was revealed, and the six-element sequence had to be memorized; the other half of the participants did not receive these instructions (incidental-learning group). For all participants, the experiment ended with an interview, during which they were asked whether they had noticed a task sequence when performing the experiment, and, if so, what that sequence was. If participants could not remember the sequence, they were encouraged to guess. The experiment took about 40 min.

Design

The independent within-subjects variables were condition (i.e., $n - 2$ task repetition vs. nonrepetition) and predictability (predictable vs. random). Group (instructed vs. incidental) was a between-subjects variable. The dependent variables were RT and error rate. The measure of task-sequence-specific learning was calculated by averaging performance in Blocks 5, 7, 8, and 10 (predictable-sequence blocks) and subtracting this value from the average of the Blocks 6 and 9 (random-sequence blocks). (Block 10 was included in this calculation to correct the learning measure for unspecific practice effects.) Task inhibition was measured by subtracting performance in individual trials that were $n - 2$ nonrepetitions (e.g., CB*A*) from performance in trials that were $n - 2$ repetitions (e.g., AB*A*).

RESULTS

The interview data revealed that no participant in the incidental-learning group became aware of a predictable sequence. However, the learning effect of 28 ms in that group was clearly significant, $F(1, 39) = 5.130, p < .05, \eta^2 = .116$, replicating results of previous studies exploring incidental task-sequence learning (e.g., Gotler et al., 2003; Koch, 2001). In the instructed-learning group, all participants were made aware of the task sequence prior to performing the experiment, but only 16 participants in this group were able to correctly report four or more of the tasks in the correct order during the interview. Thus, it appears that 24 participants in the instructed-learning group did not make use of the sequence information they were given and, consequently, did not form an explicit representation of the task sequence. It is not unlikely that some of these participants had fragmentary explicit knowledge of the sequence at the awareness threshold, despite the failure to express this knowledge verbally (cf. Dienes & Berry, 1997). However, because we hypothesized that chunking is a mechanism that is closely related to explicit learning, we retained for further analysis only those 16 participants who were able to verbally report the sequence (instructed-aware group). That is, we compared performance of the 40 participants in the incidental-learning group (who were unaware of a sequence) with performance of the 16 participants in the instructed-aware group in order to focus on the effect of the formation of explicit task-sequence representations on task inhibition.

For this further analysis, we discarded the first two trials of each block and analyzed only trials that were preceded by at least two trials with correct responses. All errors were excluded from the RT analysis. Because time of the transfer test (i.e., Block 6 vs. Block 9) did not interact significantly with the group variable, we report only the data collapsed across the two transfer tests.

For error rates, we ran a mixed analysis of variance (ANOVA) with the variables of predictability, condition, and group. This ANOVA revealed a significant effect of condition, $F(1, 54) = 8.89, p < .05, \eta^2 = .141$; error rates were higher in $n - 2$ task repetitions (4.5%) relative to nonrepetitions (3.4%), resulting in an inhibition effect of 1.1%. The inhibition effect did not differ significantly between groups, $F(1, 54) = 3.5, p > .07, \eta^2 = .061$, even though the $n - 2$ repetition cost was slightly higher overall in the instructed-aware group. All other effects were not significant ($Fs < 1$). Because the pattern of error rates did not contradict the interpretation of the RT data, we focused on the RT data.

For trials with correct responses preceded by at least two other correct trials, RTs greater than 4,000 ms were discarded (< 1.7%). The ANOVA revealed significant main effects of predictability and condition, $F(1, 54) = 22.7, p < .05, \eta^2 = .30$, and $F(1, 54) = 72.1, p < .05, \eta^2 = .57$; the benefit of sequence-specific learning was 108 ms (1,305 ms vs. 1,413 ms), and the
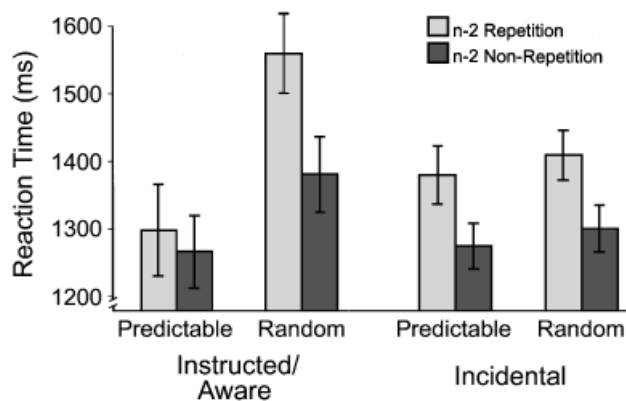
Fig. 1. Reaction time as a function of predictability (predictable vs. random task sequence), condition ($n − 2$ task repetition vs. nonrepetition), and group (incidental-learning vs. instructed-aware). Errors bars represent standard errors.

inhibition effect was 106 ms (1,412 ms vs. 1,306 ms). Predictability interacted significantly with condition, $F(1, 54) = 5.438$, $p < .05$, $\eta^2 = .091$, and with group, $F(1, 54) = 12.5, p < .05, \eta^2 = .188$, but these two-way interactions were qualified by a three-way interaction of group, predictability, and condition, $F(1, 54) = 4.75$, $p < .05$, $\eta^2 = .08$. That is, in the instructed-aware group, the inhibition effect was 147 ms smaller in predictable than in random task sequences (32 ms vs. 179 ms), whereas in the incidental-learning group, the inhibition effect was only 4 ms smaller in predictable than in random sequences (105 ms vs. 109 ms; Fig. 1). No other effects were significant ($Fs < 1$).

DISCUSSION

Learning the structure of the task sequences in the present study necessitated forming associations at least on the level of triplets. That is, the upcoming task could be predicted from the current task only if the preceding task was also taken into account (i.e., there were no unique task transitions; cf. also Keele et al., 2003; Koch, 2001). The effect of task-sequence learning in this study thus demonstrates that participants formed a rather complex higher-order representation of the task sequence. This suggests that participants did not represent each task individually, but rather, put tasks in the context of other tasks, which apparently facilitated task performance.

What is the nature of the representations underlying the sequence-learning effect? We argue that it is the sequence of tasks that is learned. An alternative possibility is that participants learn a perceptual sequence of cues that is correlated with the task sequence (see Mayr & Kliegl, 2003, for a discussion of the dissociation of cues and task sets). However, in a recent study on incidental task-sequence learning, Gotler et al. (2003) used two different cues for each task, so that the predictable task sequence was associated with a random cue sequence, and found that the learning effect was just as strong as with a unique cue-task mapping relation. This suggests that the sequence-learning

effect is not due to facilitated cue encoding, but rather is due to facilitated activation of the next task goal.

Previous studies focused on the effects of learning on shift costs, and these studies found that learning did not affect shift costs (e.g., Gotler et al., 2003; Koch, 2001). In contrast, the present study focused on task inhibition, and we also found that under incidental-learning conditions, task-sequence learning did not influence task inhibition. However, because we assumed that explicit sequence awareness would be necessary to induce chunking of the task sequence, we gave half of the participants explicit information regarding the to-be-performed sequence. About one third of these participants (16 of 40) developed (and maintained) an explicit representation of the task sequence. For these participants, we found a clear modulation of the inhibition effect, measured as reduced cost in $n − 2$ task repetitions, as a function of task predictability.

To explain this finding, we suggest that explicit instruction about a task sequence with $n − 2$ repetitions leads to spontaneous chunking based on those repetitions. In such chunks, performance of the within-chunk elements should be facilitated relative to performance at the chunk boundary (e.g., Koch & Hoffmann, 2000). If participants form such chunks, performance should be facilitated in the $n − 2$ task repetitions as compared with random sequences, in which there are no chunks. The result of this presumed chunking process would be a reduced inhibition effect. In contrast, when participants are not explicitly informed about the sequence, it is less likely that they spontaneously form such chunks, so that any learning benefit would be the same for $n − 2$ repetitions and nonrepetitions.

The finding that sequence learning did not affect inhibition in the incidental-learning group suggests that inhibition is most likely tied to task-implementation processes, such as S-R rules (Mayr & Kliegl, 2003; Schuch & Koch, 2003). In contrast, task-sequence learning probably operates at the level of priming of task goals (e.g., "perform a color judgment"), which is only the first step in activating the entire task set (see also Gotler et al., 2003; Rubinstein, Meyer, & Evans, 2001). We assume that the hypothesized chunking process primes particularly those goals that refer to the $n − 2$ task repetitions, which are located within a chunk. If that is correct, the reduction of the task-inhibition effect in the instructed-aware group is not truly a modulation of the task-inhibition process, but rather is a selective facilitation effect for those task goals that refer to the $n − 2$ repetitions.

Generally, though, the instructed-aware group did not seem to have an overall benefit in task performance relative to the incidental-learning group. That is, the instructed-aware group showed an overproportional increase of RT in trials with $n − 2$ task repetitions in random task sequences, but this increase might reflect an interference effect in random tasks rather than a facilitation effect in predictable tasks. This is a very difficult issue to resolve because, relative to the incidental-learning group, the instructed-aware group showed neither a significant relative reduction of the task-inhibition effect in the predictable

blocks ($p > .24$) nor a significant relative increase in this effect in the random blocks ($p > .19$).

In fact, this difficulty in obtaining valid baselines for between-groups comparisons also makes it difficult to analyze the hypothesized chunking process in more detail in the present study. That is, if we analyze RT as a function of the six serial positions within the predictable sequence, we mainly see generally reduced RT differences between $n - 2$ repetitions and $n - 2$ nonrepetitions in the instructed-aware group relative to the incidental-learning group (i.e., exactly as in the overall analysis), but it is not possible to pinpoint statistically significant group differences in chunking strategy. This difficulty is presumably due to the reduced effect size when the random sequences (for which serial positions are difficult to define) are omitted from the analysis and to the increased variances that result from the reduced number of observations for each data point in this detailed analysis. It appears most reasonable theoretically that the obtained three-way interaction was largely due to a chunking-based facilitation effect selectively acting on the $n - 2$ task repetitions in the blocks with the predictable task sequence, even though future studies will have to corroborate our specific chunking hypothesis.

The idea of a task-chunking process seems to be an intriguing hypothesis for further empirical testing. The literature already contains suggestive evidence for the existence of order sets (Luria & Meiran, 2003) or hierarchical task structures (Lien & Ruthruff, 2004), but these studies either manipulated the repetition or switch of only a pair of tasks (Luria & Meiran, 2003) or introduced spatial or temporal variations in the presentation of the task stimuli (Lien & Ruthruff, 2004). In contrast, the idea of task chunking based on the pattern of relations in the task sequence (cf. Koch & Hoffmann, 2000) offers a new opportunity for exploring task representations that go beyond an individual task (see also Logan, 2004). Given that tasks are rarely, if ever, performed in isolation, the mechanisms of forming representations of entire task sequences will be an important new topic for future research on executive control.

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