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Nonintentional task set activation: Evidence from implicit task sequence learning

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Studies have shown that task sets could be configured endogenously (i.e., on the basis of memory) according to an explicit sequence or exogenously according to a task cue. In two experiments, we examined whether an implicitly learned sequence could facilitate task set configuration without participants' intention. These experiments led to opposite conclusions regarding this question, but their methodology made it impossible to distinguish between the interpretations. We altered the task-switching paradigm by embedding a hidden task sequence, while randomizing all other aspects, including perceptual (i.e., task cues) and motor elements. We found that a sequence of tasks, proper, was learned implicitly and that the memory of that sequence endogenously facilitated task decision processes without the participants' explicit knowledge.

Cognitive science has recently focused on executive/control processes that supervise the selection, initiation, execution, and termination of tasks. Researchers of executive functions use the concept of task set to describe the combination of processes and actions that defines a task (e.g., Allport, Styles, & Hsieh, 1994; Meiran, 1996; Rogers & Monsell, 1995). A task set can include an array of possible stimuli, responses, mappings between them, and so forth. When one switches to a new task, a new task set must be reconfigured, and possibly, the previous task set needs to be inhibited (Mayr & Keele, 2000).

One of the most popular paradigms for studying task set reconfiguration is task switching (Allport et al., 1994; Jersild, 1927; Rogers & Monsell, 1995), in which participants respond to a target stimulus according to two or more task rules, which may or may not change from trial to trial. For instance, a number is presented, and participants must either decide whether the number is odd/even or decide whether the number is greater/smaller than 5, and in each trial participants need to make one of these simple decisions (Sudeven & Taylor, 1987). Different versions of this paradigm have highlighted different mechanisms for initiating task set reconfiguration. For example, in the alternating-runs paradigm (Rogers & Monsell, 1995), participants perform the two tasks (A and B) according to a repeated preinstructed sequence (i.e., AABBAABB . . .). Because the task sequence is known to the participants in advance, Rogers and Monsell claimed that they reconfigure task sets endogenously (i.e., in a memory-based fashion) and intentionally. In contrast, in the cuing version of the task-switching paradigm (see Figure 1 and Experiment 1 for more details; see also de Jong, 1995; Meiran, 1996; Shaffer, 1965), the order of tasks is random, and participants are instructed by an external task cue which task rule to apply in each given trial. Accordingly, task set reconfiguration is considered as involving exogenously (in this case, cue-based) initiated processes. The present work provides evidence of an endogenous task set reconfiguration process, triggered or primed implicitly by a learned sequence of tasks.

Participants performed the cuing task-switching paradigm presented in Figure 1 and were led to believe that the tasks were ordered randomly. However, a repetitive sequence was embedded in the task assignment structure. In other words, we combined the task-switching paradigm with the implicit sequence-learning paradigm (Willingham, Nissen, & Bullemer, 1989). In the present experiments, each trial included an instructional cue indicating which one of two possible tasks were to be performed on the following target stimulus. Typically, tasks and target stimuli (and therefore, the responses) are ordered randomly; however, in the present experiments, there was a fixed order of tasks. Still, because the target stimuli were determined randomly within each task, the sequence of target stimuli and the sequence of responses were both random.

Two recent works have employed a similar manipulation. Koch (2001) found that participants learned incidentally the sequence of tasks, as shown by increased response times (RTs) in the random-sequence condition, as compared with the sequenced condition. The author concluded that task set could be activated automatically by the implicit knowledge in the learned sequence. Heuer, Schmidtke, and Kleinsorge (2001) also included a sequence of tasks in the task-switching paradigm in order to evaluate the role of implicit knowledge in triggering endogenous task set reconfiguration processes. The latter authors also found evidence for sequence learning (Experiments 1 and 2) but attributed this effect to learning the sequence of task cues,

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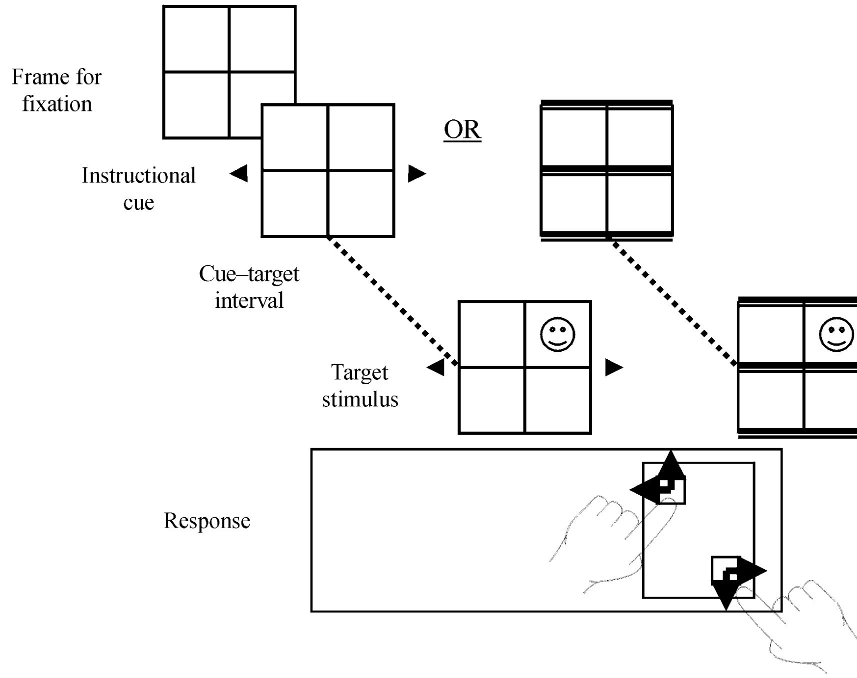

Figure 1. The experimental paradigm presented for the right–left task and the "3" and "7" keys group.

which, in their design, were target locations and target colors. Note that Koch and Heuer et al. presented very similar findings, yet they reached opposite conclusions. The reason for this somewhat paradoxical state of affairs is that the results are equally interpretable in both ways, because each task was cued by a unique task cue and, therefore, the sequences of tasks and of task cues were perfectly correlated.

Both theoretical interpretations are grounded in the literature on implicit sequence learning. Heuer et al.'s (2001) interpretation is supported by studies showing that participants can learn a sequence of stimuli and locations (Howard, Mutter, & Howard, 1992; Mayr, 1996; Stadler, 1989). This interpretation can be challenged, however, with the results of other studies that have shown that sequence learning could not be based exclusively on the sequence of target stimuli (e.g., Willingham, 1999; Willingham et al., 1989; Ziessler, 1994). Koch's (2001) conclusion relies on an ability to learn a sequence of more abstract representations—in this case, representations of tasks. This view can be supported by Jiménez and Méndez (1999), who argued that participants learn the sequence of any task elements that are represented in working memory, even if abstract in nature. On the basis of the latter claim, it is quite reasonable to assume that participants will learn the sequence of tasks, proper, because tasks, or the goal states, are represented in working memory (e.g., Rubinstein, Meyer, & Evans, 2001).

In this work, we address the dispute between Heuer et al.'s (2001) position and Koch's (2001) position by eliminating the correlation between task ordering and task cue ordering. This was achieved by randomizing all experimental aspects apart from the tasks themselves. Thus, we provide much more conclusive evidence than was previously available concerning participants' ability to implicitly learn and implement a task sequence.

EXPERIMENT 1

The present experiment (Figure 1) included two tasks requiring a position judgment of a target stimulus: one along the vertical axis (Task V: "Is the target *up* or *down*?"), and the other along the horizontal axis (Task H: "Is the target *right* or *left*?"). The participants were presented with a 2 × 2 grid, followed by a cue that instructed which of the two tasks to perform, followed by the target stimulus. Although the participants were led to believe that the tasks were ordered randomly, the tasks were assigned according to a fixed sequence. As in other studies on sequence learning, a slowing in performance when this sequence was replaced by another ("random") sequence indicates that learning had occurred.

Unlike in Heuer et al.'s (2001) and Koch's (2001) experiments, the tasks were the only sequenced element. Accordingly, for half of the participants, one of two randomly selected, different cues cued each task. For this group, task order was the only sequenced element, whereas cue order, as well as all other task elements, were randomly ordered. In addition, a control group for which each task was cued by a single cue was included in order to replicate Koch's and Heuer et al.'s findings in our paradigm. For this group, in addition to the sequence of tasks, a sequence of task cues could potentially also be learned. A sequence-learning effect in both groups would support the learning mechanism proposed by Jiménez and Méndez's (1999) and Koch's interpretation, whereas a sequence-learning effect in the constant-cues group only would support the unique role of concrete task elements in sequence learning and Heuer et al.'s conclusion.

Method

Participants

Sixteen undergraduate students from Achva College, affiliated with Ben-Gurion University, participated in a 1-h session for partial course credit. Responses were collected on the numeric keypad area of the keyboard. Half of the participants were assigned to respond with an upper-left key ("7") indicating *up* or *left*, depending on the task, and with a lower-right key ("3") indicating *down* or *right*. The other half used the lower-left key ("1") and the upper-right key ("9"). In addition, half of the participants had only one set of cues to indicate which task to perform, and the other half had two sets of cues that were randomly assigned.

Apparatus and Stimuli

The stimuli were drawn in white on black, included a 2×2 grid in the middle of the screen, and subtended a visual angle of approximately 3.4º (width) $\times$ 2.9º (height). The target was the smiling-face character, subtending approximately 0.3º (width) $\times$ 0.5º (height). There were two types of cues. (1) Two arrow heads pointed either up and down to indicate the up–down task or right and left to indicate the right–left task. The arrows subtended approximately 0.3º $\times$ 0.3º and were positioned 0.7º from the end of the grid. (2) The thickness of either the vertical lines of the grid, to indicate the up–down task, or the horizontal lines, to indicate the right–left task, were doubled (see Figure 1).

Procedure

The participants received written instructions, which were followed by a short practice session (20 trials) and by the experiment itself. Errors were signaled by a 400-Hz beep for 50 msec. A short break was introduced at the end of the practice session and at the end of each experimental block. There were nine experimental blocks that consisted of 168 trials each (except for the last block, which consisted of 88 trials). The tasks in the first block were in a fixed sequence that was 8 trials long and contained the same proportion of switch and no-switch trials. The other eight blocks consisted of 80 fixed-sequence trials followed by 8 "random" trials (with the same proportion of switch trials) and ended with another 80 sequenced trials, except for the last block, which had only the first two parts (88 trials). The eight-element sequence was VHHVVVHH. The "random" sequence that replaced it was HVVHHHVV.

In each trial, target position was selected on a random basis, with equal probabilities. A trial consisted of (1) the presentation of an empty grid for fixation for 1,000 msec, followed by (2) the instructional cue presented for a cue–target interval of 100 msec. This was followed by the presentation of the target stimulus, which remained visible until the response was given. After the experiment was finished, the participants answered the following questions. (1) "Did you notice any regularities in the experiment?" (2) "Did you notice a repeating task sequence?" (3) "There was a task sequence in the experiment. Could you repeat it?"

Analytic Method

Each of the nine experimental blocks was divided into three mini-blocks (except for the last block, which included two mini-blocks). The mini-blocks corresponded to the first 80 trials from each block (sequenced), the following 8 trials (random in all but the first block), and the last 80 trials in a block (sequenced, but present in all but the last block). This created 26 mini-blocks, of which some were sequenced and some were random. By comparing the random and the sequenced blocks, we assessed the sequence-learning effect.

The following trials were excluded from analysis: (1) the first trial in each block, because it had no switching status; (2) trials immediately following an error, since it could not be determined which task was performed in the erroneous trial and, therefore, it was not possible to determine whether the current trial was a switch or a nonswitch trial; and finally, (3) trials associated with errors, which were analyzed for accuracy only. In the main analysis, each condition was represented by the mean, after trials with responses faster or slower than two standard deviations of that mean were trimmed.

Design

Cue assignment (constant cues vs. varied cues) was manipulated between subjects, Mini-block (26 levels) and task switch (switch vs. no switch) were within-subjects variables.

Results and Discussion

Explicit Learning

The participants' explicit knowledge was accessed by verbal report, and not a single participant reported noticing the sequence. In most cases, the participants noticed some sporadic incidents in responses or targets location, such as, for example, a sequence of five responses on the same key or the same target for a few trials.

Response Times

We conducted a three-way analysis of variance (ANOVA) according to cue assignment, mini-block, and task switch. Mini-block and task switch showed significant main effects [$F(25,350) = 41.21$, $MS_e = 31,886$, $p < .0001$, and $F(1,14) = 28.95$, $MS_e = 31,886$, $p < .0001$, respectively]. In order to assess sequence learning, we compared the random mini-blocks to the sequenced mini-blocks, while excluding the first block from the analysis, since it was completely sequenced (see Figure 2). This focused comparison indicated that RT in the random mini-blocks (835 msec) was significantly longer than RT in the sequenced mini-block [804 msec; $F(1,14) = 11.81$, $MS_e = 20,595$, $p < .005$]. The only significant interaction involved mini-block and task switch [$F(25,350) = 1.82$, $MS_e = 16,716$, $p < .05$]. This interaction reflected the gradual decrease in switching cost because of training (e.g., Meiran, 1996; Rogers & Monsell, 1995). Importantly, the interaction between the sequence-learning contrast and task switch was nonsignificant [$F(1,14) = 1.35$, n.s.]. In addition, the interaction between the sequence-learning contrast and cue assignment was nonsignificant [$F(1,14) = 0.004$], since the sequence-learning effect was almost the same for the varied-cues group (29 msec) and the constant-cues group (33 msec). More important, the sequence-learning contrast in the varied-cues condition was significant [$F(1,14) = 7.69$, $MS_e = 20,595$, $p < .05$].

Proportion of Errors (PE)

The overall percentage of errors (PE) was very low (.023). The only significant effects were the main effects of cue assignment (varied group PE > constant group PE)

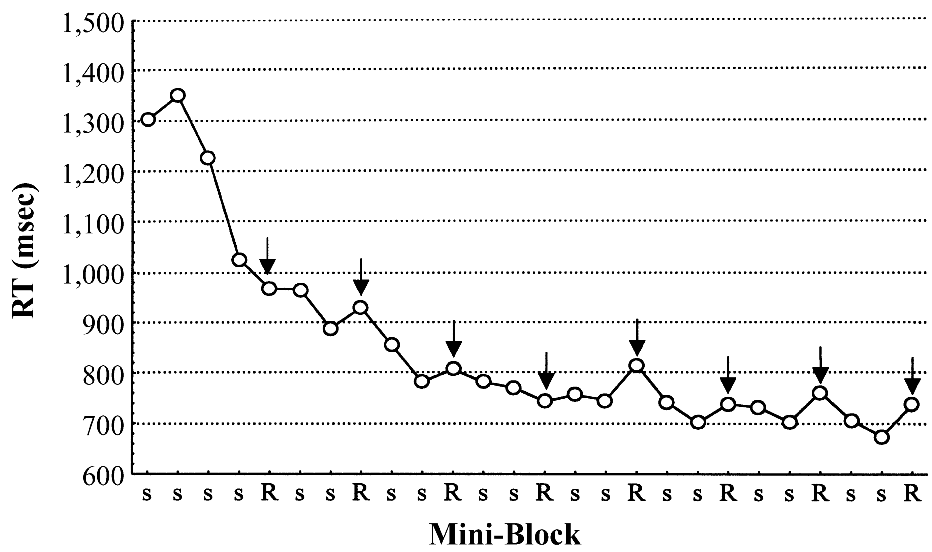

Figure 2. Mean response times (RTs) according to mini-block in Experiment 1. S, sequenced; R, random. The arrows are pointing to the random mini-blocks.

and task switch (switch PE > no-switch PE). Importantly, the mini-block variable and, specifically, the sequence-learning contrast did not have a significant effect, nor did they interact with any other variable. The numerical trend indicated that the sequence-learning effect was not modulated by a speed–accuracy tradeoff, since the PE was slightly lower in the random mini-blocks (.0176) than in the sequenced mini-blocks (.025).

The present results support the interpretation that sequence learning was based on task sequence, and not exclusively on task cues, for two reasons: First, the sequence-learning effect in the varied-cues group was significant, and second, it was numerically almost equal (and the same, statistically) in both groups. It is difficult to determine whether the constant-cues group learned the sequence of cues, of tasks, or of both. However, the findings suggest that the presence of a cue sequence did not create an advantage over learning the task sequence. The nonsignificant interaction between the sequence-learning contrast and task switch indicates that the processes that benefited from the learning were common to both switch and no-switch trials. This pattern is consistent with Koch's (2001) and Heuer et al.'s (2001) findings, and its implications will be discussed later.

EXPERIMENT 2

In Experiment 1, as in Koch's (2001) study, explicit knowledge was assessed by an interview. The problem is that one could argue that the participants had explicit knowledge of the task sequence but failed to report it. In this case, the paradigm resembled the *alternating-runs* paradigm (Fagot, 1994; Rogers & Monsell, 1995), because the participants performed the tasks according to an explicitly known sequence. Experiment 2 used a more sensitive measure of explicit knowledge in order to show that participants can implement a task sequence without having explicit knowledge of it.

There is a controversy in the sequence-learning literature regarding direct and indirect methods for measuring explicit knowledge (Dienes & Berry, 1997; Shanks & St. John, 1994), and the prevalent conception regards reportability as an insufficiently sensitive measure of explicit knowledge. Therefore, the aim of Experiment 2 was to replicate the crucial condition of Experiment 1 (random cues), and it also included a generation task, considered to be sufficiently sensitive to assess explicit knowledge (Destrebecqz & Cleeremans, 2001; Dienes & Perner, 1999; Perruchet & Amorim, 1992; Shanks & St. John, 1994).

Method

Participants

Sixteen undergraduate students from Ben-Gurion University participated in two 1-h sessions for partial course credit. Two participants were eliminated from the final analysis due to a high error rate (15%, as compared with 8% in the next worst participant).

Procedure and Analytic Method

The only differences relative to Experiment 1 were that (1) the last block in each session included three mini-blocks, rather than just two, so that the middle mini-block was random and the two surrounding mini-blocks were sequenced, and (2) there were two different sequences, counterbalanced across participants, rather than just one sequence. These were 1-VHHVVVHH and 2-HVVHHHVV. One sequence was repeated, and the other sequence served as the "random" sequence.

After the interview, there was a generation task. In the generation procedure, the participants were told that the tasks in the previous pair were ordered according to a repeating sequence of 8 tasks long. The participants were given 40 trials similar to the experimental trials, but without introducing the task cues, and were asked to perform whichever task they thought was appropriate according to the sequence, while emphasizing accuracy. In order to identify which task the participants had in mind, the response keys of the two tasks were separated in this stage of the experiment. Therefore, the participants used the numeric keypad keys "6" and "3" for the up–down task and the keys "1" and "2" for the right–left task. These keys more or less preserved the spatially compatible keys used in the preceding part of the experiment, in the sense that the upper key indicated *up*, the lower key indicated *down*, and so forth.

In addition, the random mini-block in Experiment 1 was always in the middle of the block, meaning that the sequence-learning effect was confounded with serial position effects. Specifically, a general slowing in the middle of the blocks could explain the longer RT in the random mini-blocks. Hence, a serial position analysis was included to rule out this alternative explanation.

Results

Explicit Learning

Interview. As in Experiment 1, the participants' reportable knowledge was tested, and none of them had noticed the task sequence.

Generation task. In order to assess task sequence knowledge, we simulated 16,000 participants that generated a random sequence of 40 tasks by using a uniform distribution (equal probability for both tasks) and calculated the number of correctly produced task triplets. The mean number of correct simulated triplets was 3.8, with an *SD* of 3.0. In addition, we counted the number of triplets of tasks that the participants managed to reproduce correctly and compared each participant with the simulated results. To be on the safe side, actual participants whose number of correctly produced triplets exceeded one standard deviation or above the mean simulated number of triplets (more than 7 correct triplets) were "suspected" of having some explicit knowledge. We identified 5 participants who could be classified as such, and therefore, in the RT analysis, the participants were separated into two groups according to level of explicit knowledge: no explicit knowledge (between 0 and 7 correct triplets) versus suspected explicit knowledge (between 8 and 10 correct triplets).

Response Times

Since session did not interact with the sequence-learning contrast, its effects are not reported below. The participants were grouped into two *knowledge* groups (see above), and we conducted a 2 × 27 × 2 ANOVA that included the independent variables of knowledge group, mini-block, and task switch. Only the main effects of mini-block and task switch were significant [$F(20,240) = 31.25$, $MS_e = 22,293.8$, $p < .0001$, and $F(1,12) = 13.57$, $MS_e = 70,099.5$, $p < .005$, respectively]. In order to assess sequence learning, we compared the random mini-blocks with the sequenced mini-blocks, while excluding the first block from the analysis, since it was completely sequenced. The comparison indicated that RT in the random mini-blocks (687 msec) was significantly longer than RT in the sequenced mini-block [655 msec; $F(1,12) = 7.17$, $MS_e = 28,337$, $p < .05$].

The focused contrast estimating the interaction between the sequence-learning contrast and knowledge group was nonsignificant [$F(1,12) = 1.17$]. However, the sequence-learning contrast in the group *without* explicit knowledge (45 msec) was significant [$F(1,12) = 9.89$, $MS_e = 28,337$, $p < .01$], whereas this contrast in the group *with* explicit knowledge (19 msec) was nonsignificant [$F(1,12) < 1$;

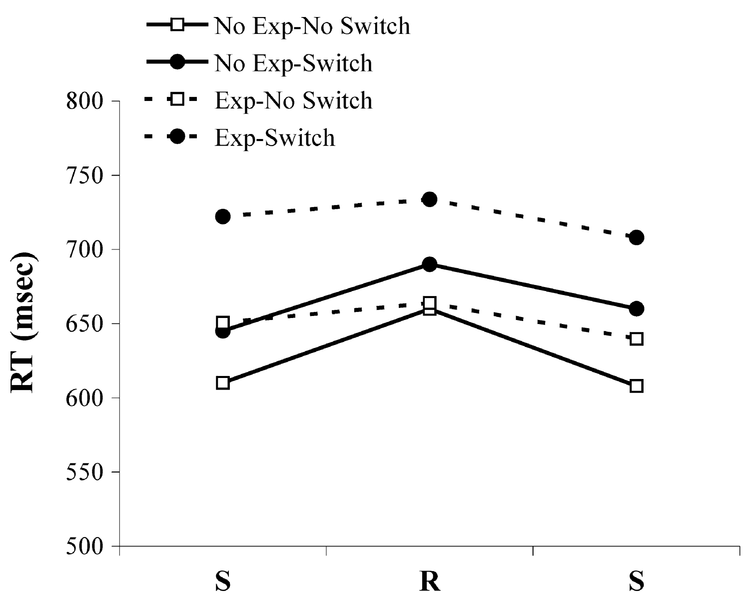

Figure 3. Mean response times (RTs) in first, last, and middle mini-blocks averaged across blocks (first block excluded) and sessions, according to explicit knowledge and switch in Experiment 2. Exp, explicit knowledge group; No Exp, no explicit knowledge group; S, sequenced; R, random.

see Figure 3]. Mini-block interacted with task switch [$F(1,12) = 2.11$, $MS_e = 9{,}160$, $p < .01$]. As in Experiment 1, task switch did not interact with sequence learning [$F(1,12) < 1$]. The serial position analysis (which was conducted regardless of knowledge group) compared the eight trials in the beginning and the end of the block (718 msec) with the eight trials just preceding or coming immediately after the "random" trials in the middle of the block (711 msec). This nonsignificant [$F(1,12) < 1$] trend was inconsistent with the alternative, serial position explanation, since RTs in the middle of the block were relatively shorter.

Proportion of Errors

The overall PE was .03, and the trend for the sequence-learning contrast was similar to that found for RT.

GENERAL DISCUSSION

The present experiments support Koch's (2001) interpretation that a sequence of tasks could be learned and implemented without participants' explicit knowledge. We found that responses were faster under the sequenced condition, as compared with the random condition. This learning was based exclusively on the sequence of tasks, since it was the only nonrandom element in the experiment. It is unlikely that the learning effect reflected facilitated cue processing, since the design prevented learning on the basis of the task cue sequence (the varied-cues group in Experiments 1 and 2). Furthermore, results from a yet unpublished work show similar effects with a cue–target interval of 900 msec. In such a time frame, cue processing is probably completed before the target is presented in both sequenced and random trials, making it highly unlikely that facilitated cue processing was responsible for the sequence-learning effect.

The sequence learning and the resulting knowledge were implicit in the sense that the gained knowledge could not be reported by participants and did not transfer to the generation task. This definition is consistent with recent approaches for identifying implicit knowledge. First, a key criterion for implicitness, according to Dienes and Berry (1997), is that implicit knowledge is inflexible in transfer to other domains. At the extremes, totally implicit knowledge, like procedural knowledge, is completely specific to a given situation, whereas totally explicit knowledge could be transferred to representations in the lexical system—meaning that it could be verbalized (Dienes & Perner, 1999). In a complementary fashion, Perruchet and Vinter (in press) claimed that transfer of knowledge from the original situation (i.e., learning) to another situation (i.e., generation task) is possible only when the elements that are common to both situations (i.e., the task sequence) are conscious. In that sense, the lack of transfer to the generation task in Experiment 2 implies that the gained knowledge was implicit. One could claim, however, that our generation task, which employed a change in response keys, was sufficiently different from the experimental situation to create an inappropriate transfer situation. Nonetheless, Stadler (1989) found that changing the response apparatus from the learning phase did not decrease performance, meaning that knowledge could be transferred to a setup involving different responses. Moreover, the group that showed larger transfer (explicit knowledge group) had a numerically smaller (and nonsignificant) learning effect than did the group with lesser transfer. Thus, we find it very unlikely that the sequence-learning effect we observed was modulated by explicit knowledge.

An interesting question is which task reconfiguration processes were affected by sequence learning. Like Heuer et al. (2001) and Koch (2001), we found that sequence learning did not alter the switching cost, so that the gain from sequence learning was statistically equal in switch and no-switch trials. On the basis of this result, Koch claimed that the sequence learning of tasks leads to "more or less automatic 'priming' of task-sets that is not mediated by intentional processes"(p. 1478). We suggest that, in the cuing version of the task-switching paradigm, one component of task set reconfiguration involves deciding which task to execute. Because of the random ordering of tasks in the cuing paradigm, such task decision processes must be performed in both switch trials and no-switch trials. Accordingly, we suggest that task sequence learning reduces task uncertainty and facilitates task decision processes in switch and no-switch trials similarly. This interpretation is supported by recent results by Ruthruff, Remington, and Johnston (2001; see also Sohn & Carlson, 2000) that manipulated task expectancy by using a simple sequence (AABB) and occasionally diverging from the expected sequence. They found that expectancy effects were additive with the task-switching effects and concluded that task expectancy modulates the "time required to complete the programming of the upcoming central mental operations" (Ruthruff et al., 2001, p.1418). These results and interpretation are similar to ours; however, the crucial difference between the two studies is that in Ruthruff et al.'s study, the participants were explicitly informed about the very simple task sequence, whereas in the present study, this knowledge was implicit.

It is important to note that the sequence did not determine which task to perform, since the participants eventually performed the correct task even when it contradicted the learned sequence (as seen by similar PEs in sequenced and random trials). Therefore, the final task decision must have been made intentionally, according to the instructional cue. This observation is consistent with a dual-mechanism activation model for task decision: a fast nonintentional mechanism that prioritizes tasks and is sensitive to implicit knowledge, and an intentional mechanism that makes the final decision. Task decision is faster if the cued task is already activated by the fast nonintentional mechanism than if the competing task is activated. Similar claims already exist in the literature. For example, Norman and Shallice (1986) proposed "contention scheduling" as a fast nonintentional system for selecting schemas and a "supervisory attentional system" as an intentional selecting mechanism.

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