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Spatial interference and response control in sequence learning: the role of explicit knowledge

Abstract In several sequence learning studies it has been suggested that response control shifts from the stimuli to some internal representation (i.e., motor program) through the learning process. The main questions addressed in this paper are whether this control shift is related to explicit knowledge and whether the formation of these internal representations depends on the stimulus attributes. In one experiment we compared the learning of a response sequence triggered by either spatial location or location symbol (left-right) by using a serial response task (SRT). Symbols were presented at either a centered or random location. The results showed that in the symbolic conditions the shift of response control correlated with the emergence of explicit knowledge. Only participants with complete explicit knowledge seemed to learn the sequence structure beyond probabilistic information (response time "RT" did not depend on the frequency of the response). Moreover, these participants were able to overcome, when needed, spatial interference (RT was the same for both spatially corresponding and non-corresponding trials). However, when spatial location was relevant, RT was always faster, especially for more frequent responses. These results suggest that the relevant stimulus dimension (location or symbol) seems to engage different sequence learning mechanisms.

Introduction

One of the questions addressed in learning studies using serial response tasks (SRT) is whether learning is based mainly on the structure of the stimulus sequence or on the structure of the responses (i.e., sequences of key-presses). In order to analyze the contributions from perceptual and motor information, spatial and nonspatial attributes have been used. Whereas stimulus and response locations usually correspond when space is relevant, responses are arbitrarily assigned to intrinsic perceptual attributes (i.e., color; Willingham, Nissen, & Bullemer, 1989; shape; Mayr, 1996) or symbols (i.e., digits; Helmuth, Mayr, & Daum, 2000) when nonspatial sequences are involved.

The study of the effects of different stimulus attributes might be especially relevant for understanding the different connections between stimuli and responses. Specifically, comparisons between spatial and nonspatial stimulus sequences could provide useful information about the locus of response control. It has been suggested that response control shifts from the stimuli to internal motor codes (i.e., motor programs) through the learning process (Nattkemper & Prinz, 1997; Hoffmann & Koch, 1997). These internal motor codes allow faster response times (RT) and their formation seems to correlate with the acquisition of explicit knowledge (Hoffmann & Koch, 1997; Zirngibl & Koch, 2002). In relation to the role of the stimulus, Hoffmann and Koch (1997) found no differences in RT between spatial and symbolic stimulus when the learning was explicit. In contrast, Hazeltine, Grafton, and Ivry (1997), based on PET evidence, concluded that stimulus characteristics had strong effects only in the case of explicit sequence learning. However, it is not clear from their results if the analyses were made only with the participants showing explicit knowledge or with all the "single-task" condition participants (both aware and unaware). Zirngibl and Koch (2002) also manipulated the stimulus mode (spatial and symbolic) together with the response mode (manual and verbal) showing that only response mode (and degree of explicit knowledge) had a clear effect on sequence learning. Hence, as far as we know, the role of the stimulus attributes in the formation of internal motor codes and in their translation into symbolic expressions remains unclear. The goal of this paper is to shed light upon these issues.

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Spatial and nonspatial sequence learning systems

Some studies have related the learning of spatial and non-spatial stimuli sequences with two independent systems. For example, Mayr (1996) and Helmuth et al. (2000) found that participants were able to learn a sequence of locations and a noncorrelated sequence of responses, triggered by means of four different objects, simultaneously. Moreover, Mayr's Experiment 2 showed that both sequences were learned without interference; the same amount of learning was observed when the stimuli followed only one of the sequences, leaving at random the other dimension. This lack of interference was interpreted as evidence of there being two independent learning systems for spatial and nonspatial regularities. Whereas learning of the location sequence has been related to the input system (i.e., programming of visual orientations; Posner & Rothbart, 1992), learning of the nonspatial one seems to be based on response control processes (i.e., anterior attention system; Posner, 1992).

However, learning a sequence of locations can also be considered as learning a sequence of responses (i.e., eye movements). Therefore, a common mechanism based on the programming of spatially directed movements, either eyes or limbs, could account for the learning of both types of sequences. From this point of view, what appears to be the product of learning is the knowledge of the sequence of locations to which subjects have to respond (Willingham, 1998). The results of Koch and Hoffmann (2000a) seem to support this proposal: sequence learning depended strongly on the spatial structure of either stimuli or responses. When both stimuli and responses sequences were represented by means of symbols (verbal stimulus and response) instead of spatial locations, learning was almost absent (but see Zirngibl and Koch, 2002 for different results with a shorter sequence).

Nevertheless, the common spatial-response-based mechanism cannot account for results such as those found, for example, by Mayr (1996). If learning of the nonspatial (object) sequence had been based on the spatial structure of the responses, it would have interfered with the learning of the spatial structure of the stimuli, as can be predicted from studies on spatial working memory (Logie, 1995; Lawrence, Myerson, Oonk, & Abrams, 2001). For example, Lawrence et al. found that both overt eye movements and limb movements interfered with spatial memory, suggesting that both kinds of movements share the same spatial working memory. Moreover, Koch and Hoffmann (2000a) showed that a particular sequence of key-strokes (*easy spatial-R*) was learned to a greater extent when it was triggered by symbols (Experiment 3) than by spatial locations (Experiment 1), especially in conditions in which the stimuli followed a different spatial sequence (*difficult spatial-S*). Together with the spatial compatibility explanation (discussed below) these results seem to illustrate the impossibility of learning two different spatial sequences simultaneously.

Thus, if we assume that the programming of eye movements (or attentional shifts) is the best explanation for the learning of a sequence of stimulus locations, we should look for a nonspatial mechanism for the learning of a different sequence of spatial responses, if both kinds of sequences have been learned simultaneously and without interference. Some experimental results do suggest that the representations of the nonspatial attributes of the stimulus are present in the knowledge acquired of the response sequence. For example, in Experiment 3 of Willingham et al. (1989) participants had to respond according to the color of the letter X that appeared in different locations on the screen (four colors were arbitrarily assigned to four response-keys). In the *response sequence* condition, the sequence of stimulus locations was set randomly, but the color of the stimulus followed a 10-trial repeated sequence. Results showed that the response sequence was learned when compared with a control (random location and color) condition. However, participants who had previously learned the response sequence did not show an advantage when the same response sequence was assigned to spatial locations instead of colors. In this regard, the authors concluded that object sequence learning is stimulus dependent and, therefore, it might be based on "a series of condition-action statements mapping stimuli onto responses" (Willingham et al., 1989; p. 1058).

Explicit and implicit knowledge

Nonspatial sequence learning seems to produce more explicit knowledge than spatial sequence learning. For example, Koch and Hoffman (2000a) found a high positive correlation between explicit knowledge and amount of learning when the stimuli were digits. The results of Willingham et al. (1989) and Mayr (1996) also showed a high correlation between explicit knowledge and object sequence learning (defined by either color or shape), but not between explicit knowledge and spatial sequence learning. The results of Helmuth et al. (2000) are, in part, along the same lines. Participants with Parkinson's disease (PD), unlike normal controls, failed to learn a response sequence paired with a sequence of digits shown at four different locations on the screen. Stimulus location also followed a response-independent sequence. In this case, both groups of participants (patients and controls) learned the spatial structure of the stimuli. As the authors argued, mechanisms controlling visual attention seem to be less affected in PD than processes involved in motor-output selection. Consequently, one possible explanation of the PD patient's deficit could be related to the high attentional demands selecting the motor response by means of internal, "symbolic" cues. If learning the digits sequence depended on the development of explicit knowledge, the high attentional demands of the PD patients would have interfered with such learning.

Summing up, it appears that spatial and nonspatial sequences of stimuli are learned by means of different mechanisms and that the mechanism triggered by non-spatial attributes correlates more strongly with the acquisition of explicit knowledge. Indeed, the link between stimuli and responses (S-R) when nonspatial attributes are involved is much weaker than in conditions of S-R spatial correspondence (see below). This could explain the stronger dependence on explicit knowledge of non-automatic S-R links, especially if the automatic S-R link is triggering a different response. In this regard, one way to provide further evidence of the existence of two different learning mechanisms would be in a condition of competing responses. This possibility is outlined below.

Spatial S-R compatibility

As was pointed out above, an important difference between spatial and nonspatial stimuli sequences concerns spatial S-R compatibility. The influence of spatial S-R compatibility on RT has been found in many experiments (see Lu & Proctor, 1995 for a review). In conditions where the location of the stimulus is irrelevant, responses are faster in cases of S-R spatial compatibility than in cases of S-R spatial incompatibility. The influence of task-irrelevant spatial information is known as the Simon effect (Simon & Small, 1969). In order to explain the Simon effect, De Jong, Liang, & Lauber (1994) proposed a dual-process (or dual-route) model. In a first process there is an unconditional automatic priming of the spatially corresponding response, that is, the fast automatic route. In the second process, the identification of the response based on task instructions takes place by means of a slower route. If the automatic primed response has to be inhibited an increment of RT will be observed, giving rise to the well-known Simon effect. Moreover, this effect is stronger when the stimulus and the response share modality (i.e., physical spatial stimulus-spatial motor response or verbal stimulus-verbal response; Proctor, Wang, & Kim-Phoung, 2002).

The Simon effect is a short-lived phenomenon that disappears with response times over 500 ms but which persists even with extensive practice (Eimer, Hommel, & Prinz, 1995). Thus, comparing conditions of S-R spatial compatibility and incompatibility could help in understanding the underlying learning mechanism. If learning was mainly based on the spatial structure of the responses then similar performance should be acquired as far as the same sequence of particular keystrokes is to be repeatedly executed. If, on the other hand, the spatial structure of the stimuli were basically involved, learning in a condition of spatial incompatibility would be difficult to observe, due to the persistence of the Simon effect as shown, for example, in some of the experiments of Koch and Hoffmann (2000a) explained before.

Similarly to Hoffmann and Koch (1997), the present experiment compared the learning of a response sequence triggered by either a sequence of locations or a sequence of verbal symbols. In order to study further the relationship between response control shift and the emergence of explicit knowledge, we introduced a new symbolic condition where letters referring to left and right responses were presented randomly at left and right screen locations. The letters were related to locations as in Eliassen, Souza, & Sanes (2001), where a repeating sequence of Rs (associated with right button) and Ls (associated with left button) was presented in a fixed centered position (the repeating sequence was: RLRRLLRL). We expected that learning would be much more difficult in the case of random physical location due to the Simon effect or the similar spatial Stroop interference (Lu & Proctor, 1995). As argued above, in this condition the links between both stimulus attributes (physical location and location symbol) and their corresponding response may interfere. In order to overcome this interference, learning would depend greatly on the memory of internal movement instructions symbolically coded. Consequently, if participants show similar reaction time (RT) patterns for spatial corresponding (congruent) and noncorresponding (incongruent) trials, this would strongly suggest that movements could be predicted by internal instructions. Moreover, if the development of these internal instructions correlates with the emergence of explicit knowledge, then we would expect all explicit learners, regardless of the stimulus condition, to show similar performance.

Taking into account that the response sequence used had both response repetitions and alternations, we also analyze this effect in the different stimulus condition. Bertelson (1965) found that the time to perform a given response is much shorter if that same response was performed in the preceding trial than if some other response was performed, which is the "response-repetition" effect. However, in our response sequence alternations were much more frequent than repetitions (6/8 alternations vs. 2/8 repetitions). In that respect, another goal of the present experiment was to analyze the effect of learning, either explicit or implicit, on the "response-repetition" effect.[1]

Method

Stimuli and apparatus

A serial reaction time (SRT) task presented by means of physical location (spatial condition) or location letters (symbolic conditions) was used in this experiment. The stimuli were presented on the screen of an IBM-compatible PC. For the spatial condition the letter X appeared on either the left or right of the center of the screen (distance from the center was 3.5 cm). For the symbolic conditions, stimuli were location letters (D–E; in Catalan D: Dreta (Right) E: Esquerra (Left)) presented either centered (fixed symbolic condition) or at random locations (random symbolic

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[1] We thank Iring Koch for his suggestion for similar analyses involving the sequence structure.

condition). Both the neutral letter X and the location ones (E–D) were white symbols .7 cm high on a black background. The left and right buttons of an external response-box were paired with left and right responses, respectively.

Design

The same sequence of responses was triggered by three different stimuli conditions:

1. In the spatial condition the response sequence corresponded to the physical location of the letter X
2. In the fixed symbolic condition the response sequence corresponded to a sequence of location letters (E–D) presented in the center of the screen
3. In the random symbolic condition the same sequence of location letters was presented at random left-right screen locations

In each condition, some of the participants received incidental instructions whereas the other received intentional instructions. Intentional instructions were introduced especially for facilitating the emergence of complete explicit knowledge (especially in the random symbolic condition). Along with the between factors Stimulus (Spatial, Fix-Symb, and Rand-Symb) and Instruction (Incidental and Intentional), from the analyses of the verbal protocols given by the participants (see procedure), we created a post hoc between factor: level of explicit Knowledge. Hence, the design produced six independent groups that differed from each other with regard to the Stimulus and Instruction for the first analyses, or with regard to Stimulus and Knowledge for the post hoc analyses. The within subject factors were Block of trials and Response (repetitions and alternations).

Participants

A total of 77 students from the University of Barcelona participated in this experiment in return for extra course credits: 19 participants were assigned to the spatial condition (11 with incidental instructions and 8 with intentional ones), 19 participants were assigned to the fixed symbolic condition (8 with incidental instructions and 11 with intentional ones) and the other 39 to the random symbolic one (10 with incidental instructions and 29 with intentional ones[2]). The motive for using incidental and intentional instructions was principally to facilitate the emergence of explicit knowledge (in the case of symbolic conditions intentional instructions) or to prevent it (in the case of the spatial condition incidental instructions).

Procedure

Participants in the *spatial* condition were instructed to respond with the button corresponding to the location of the letter X as fast and as accurately as possible. Participants in both the *fixed and random symbolic* conditions were instructed to respond according to the letter (D—right button, E—left button), also emphasizing accuracy and speed. Participants in the *random symbolic* condition were advised that physical location was irrelevant. For participants with incidental instructions the experiment was introduced as one exploring the effect of training on RT. Those who received intentional instructions were informed about the existence of a repeating sequence of letters or locations (depending on the SC) and their

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[2] A pilot study showed that explicit learning was very difficult to obtain in this condition even with intentional instructions (only one-third of the participants were able to write the complete sequence).

goal, in addition to responding as fast and as accurately as possible, was to try to discover the sequence. Participants had to respond with left and right index fingers for left and right buttons and they were required to rest their index fingers on the corresponding buttons. After reading the instructions, participants were presented with a block of 24 random trials for initial practice of the task. They then had to interact with the repeating sequence for 15 blocks of 48 trials each (each block contained 6 repetitions of the sequence: DEDDEEDE). A final block of 48 random trials was used to test the amount of sequence learning. Between blocks there was a pause of 5 s and the interval between the response and the next stimulus was set to 250 ms. Finally, all participants answered a questionnaire in order to test their explicit knowledge. The questions were as follows:

1. Have you noticed any repeated letter/location sequence? For affirmative answers there was the additional question
2. Can you write the sequence of letters/locations?
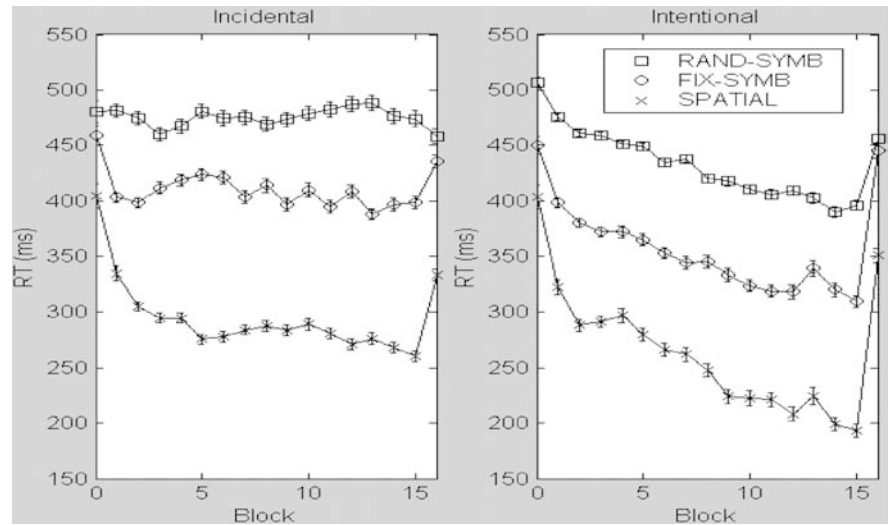
Results

Mean error rates were 4% for both symbolic conditions (for Intentional groups and for Incidental ones) and 2.5% for the spatial condition (2% for the Intentional group and 3% for the Incidental one). Given these low error rates, we did not perform any analyses with these data. Reaction times (RT) for correct responses higher than 1,000 ms were discarded. Total discarded responses (including errors) were 2.5% for the spatial condition and 4.5% for the symbolic conditions.

The effect of Instructions

Figure 1 shows the RT pattern per block split by stimulus condition for both Incidental and Intentional groups. An ANOVA was conducted on these data with Block (the 15 sequence blocks) as a within subject variable and Stimulus (Spatial, Fix-Symb, and Rand-Symb) and Instruction (Incidental and Intentional) as between subjects factors. Overall, performance across learning blocks improved significantly ($F(14,994) = 12.05$, $p < .001$). The stimulus condition also had a significant effect ($F(2,71) = 56.42$, $p < .001$). On average, participants in the Intentional groups were significantly faster than participants in the Incidental ones ($F(1,71) = 15.75$, $p < .001$). The mean RTs for the Intentional groups were 252, 352, and 433 ms for the Spatial, Fix-Symb, and Rand-Symb conditions respectively. The mean RTs for the Incidental groups were 308, 414, and 483 ms for the same conditions. While the Block × Stimulus and the Block × Instruction interactions were significant ($F(28,994) = 1.83$, $p < .005$ and $F(14,994) = 7.46$, $p < .001$ respectively), the triple interaction of these factors failed to be significant ($F < 1$). Separate analyses of each stimulus condition showed that Block was significant in both the Spatial and Fix-Symb conditions ($p < .005$) but not in the Rand-Symb one ($p > .07$). Finally, Block was only significant for the Intentional groups ($p < .005$) but not for the Incidental ones ($F < 1$).

Fig. 1 Reaction time across block split by stimulus condition and Instructions (Incidental and Intentional). Blocks 0 and 16 correspond to random blocks. Error bars show 1 ± SEM. *RAND-SYMB* random symbolic condition, *FIX-SYMB* fixed symbolic condition, *SPATIAL* spatial condition

The effect of level of explicit knowledge

In order to study the relation between explicit knowledge and response control strategies, we regrouped the participants according to their level of explicit knowledge. Explicit groups (Exp) were formed by those participants who wrote the complete sequence in the correct order; otherwise, participants were included in the non-explicit groups (NExp). Table 1 shows the percentages and raw frequencies of Exp participants in each stimulus and instruction condition. Hence, along with the Stimulus the six new independent groups were:

1. Spatial condition—NExp ($n = 9$)
2. Spatial condition—Exp ($n = 10$)
3. Fixed symbolic condition—NExp ($n = 9$)
4. Fixed symbolic condition—Exp ($n = 10$)
5. Random symbolic condition—NExp ($n = 29$)
6. Random symbolic condition—Exp ($n = 10$)

Figure 2 shows the RT pattern versus block split by stimulus condition for the NExp and the Exp groups. We conducted an ANOVA with Block (the 15 sequence blocks) as within subject variables and Stimulus (Spatial, Fix-Symb, and Rand-Symb) and Knowledge (NExp and Exp) as between subject variables. Unlike the previous analysis, the triple interaction Block × Stimulus × Knowledge was significant ($F (28,994) = 1.91$, $p < .005$). The effect of the Stimulus condition across blocks was therefore significantly affected by the level of explicit knowledge. As can be seen in Fig. 2, the Rand-Symb condition mainly contributed to this effect, since it converged to the level of the Fix-Symb condition. After removing the Rand-Symb condition, the 3-way interaction was no longer significant ($F < 1$). The analyses of the data from the Exp participants in the symbolic conditions alone confirmed this result: both Block and Block × Stimulus interaction were significant

Table 1 Percentage of participants in each group who reported the complete sequence (raw frequencies in parentheses)

	Spatial	Fix-Symb	Rand-Symb
Incidental	18 (2/11)	25 (2/8)	0 (0/10)
Intentional	100 (8/8)	73 (8/11)	34 (10/29)

Fig. 2 Reaction time across block split by stimulus condition and Level of Explicit Knowledge (*NExp* and *Exp*). Blocks 0 and 16 correspond to random blocks. Error bars show 1 ± SEM
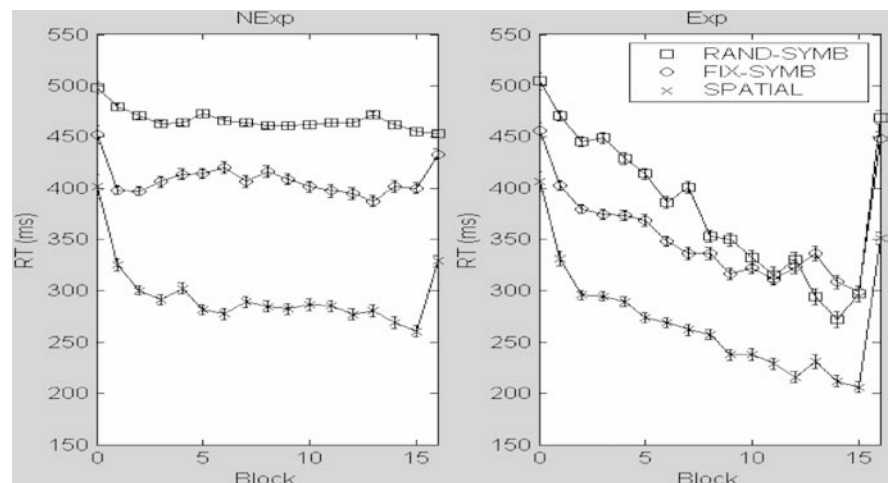
($F\,(14{,}252)\,=\,16.84$; $p\,<\,.001$ and $F\,(14{,}252)\,=\,2.28$, $p\,<\,.01$ respectively) whereas Stimulus was not significant ($F\,<\,1$). In addition, results showed an improvement through Blocks ($F\,(14{,}994)\,=\,27.98$, $p\,<\,.001$), both the Stimulus and Knowledge variables were significant ($F\,(2{,}71)\,=\,44.90$, $p\,<\,.001$ and $F\,(1{,}71)\,=\,20.08$, $p\,<\,.001$ respectively) and also both Block × Stimulus and Block × Knowledge interactions ($F\,(28{,}994)\,=\,2.12$, $p\,<\,.005$ and $F\,(14{,}994)\,=\,17.11$, $p\,<\,.001$ respectively).

In order to unconfound the learning of the sequence structure and the effect of task habituation, we ran an ANOVA with Type of Block (last sequence and transfer-random) as the within subject variable and Stimulus and Knowledge as between subject factors. The same pattern of results was obtained. Both Type of Block and the Type of Block × Knowledge interaction were significant ($F\,(1{,}71)\,=\,156.07$, $p\,<\,.001$ and $F\,(1{,}71)\,=\,91.08$, $p\,<\,.001$ respectively) and so was the triple Type of Block × Stimulus × Knowledge ($F\,(2{,}71)\,=\,3.52$, $p\,<\,.05$) interaction. RT increased significantly from the last sequence block to the random-transfer one for all Exp participants (especially in the Rand-Symb condition) but only NExp participants in the spatial condition seemed to learn (Type of Block was only significant in this NExp stimulus condition; $F\,(1{,}8)\,=\,14.11$, $p\,<\,.005$).

Sequential effects

Table 2 shows the RT means of the final sequence block and those of the transfer-random block split by Response (repetition or alternation) for the six groups. The ANOVA with Block (15 sequence blocks) and Response

Table 2 RT means (ms) in the six independent groups (NoExplicit and Explicit participants in the Spatial, Fixed-Symbolic, and Random-Symbolic conditions) in the last sequence block (*SEQ*) and in the final random block (*RAND*) for response alternations (*Alt*) and repetitions (*Rep*)

		SEQ		RAND		Difference in score	
		Alt	Rep	Alt	Rep	Alt	Rep
Spatial	NExp	242	317*	328	336	86	19
	Exp	201	215*	347	358	146	143
Fix-Symb	NExp	374	456*	433	427	61	−22
	Exp	312	273	452	439	140	166
Rand-Symb	NExp	449	466*	447	463[a]	−2	−3
	Exp	299	284	472	469	173	185

*Differences between alternations and repetitions were significant ($p\,<\,.05$). See more details in the text

[a] This effect depended on a more complex interaction between Response, Congruence, and Stimulus Location (alternation or repetition) not included in the present paper. But, in essence, this interaction showed that whereas the effect of Response (and also of Congruence) disappeared when the stimulus appeared in a repeated location, the Response effect (and also of Congruence) persisted for NExp participants in cases of location alternation (see also Notebaert, Soetens, & Melis, 2001 for a similar three-way interaction)

as within subject variables and Stimulus (Spatial, Fix-Symb, and Rand-Symb) and Knowledge (Exp and NExp) as between subjects factors showed, in addition to the results already introduced, a significant effect of Response (responses to alternations were faster than to repetitions; $F\,(1{,}71)\,=\,34.51$, $p\,<\,.001$). Both the Response × Stimulus and Response × Knowledge interactions were significant ($F\,(2{,}71)\,=\,3.91$, $p\,<\,.005$ and $F\,(1{,}71)\,=\,15.50$, $p\,<\,.001$ respectively). The triple Block × Response × Knowledge interaction was also significant ($F\,(14{,}994)\,=\,4.35$, $p\,<\,.001$). As can be read in Table 2, Response had stronger effects in NExp groups ($p\,<\,.001$) than in the Exp ones ($p\,>\,.25$). However, analyses of each stimulus condition separately showed that the Response × Knowledge interaction was always significant ($p\,<\,.01$) except in the spatial condition ($p\,>\,.16$). In the latter case, alternations were always faster than repetitions, although this effect was weaker in Exp participants.

Spatial compatibility effects

Data from the random symbolic (Rand-Symb) condition were analyzed separately in order to study spatial compatibility effects. Trials were grouped according to their congruence status: *congruent* (letter-location and physical response location corresponded; 50% of the trials) and *incongruent* (letter-location and physical response location did not correspond; 50% trials). Also, in order to study the effect of learning on the congruence effect, data from the 5 initial and the 5 final sequence blocks were grouped in two Phase factors (start and end). The ANOVA with Phase and Congruency as within subject factors and Knowledge (NExp and Exp) as a between subject factor yielded significant effects of Phase ($F\,(1{,}37)\,=\,65.56$, $p\,<\,.001$), Congruency ($F\,(1{,}37)\,=\,60.87$, $p\,<\,.001$), Knowledge ($F\,(1{,}37)\,=\,27.89$, $p\,<\,.001$), Phase × Congruency ($F\,(1{,}37)\,=\,12.87$, $p\,<\,.001$), and Phase × Congruency × Knowledge ($F\,(1{,}37)\,=\,5.93$, $p\,=\,.05$). As shown in Fig. 3, congruency had a clear effect in the first phase (5 initial blocks) in both NExp and Exp participants. On the contrary, in the last
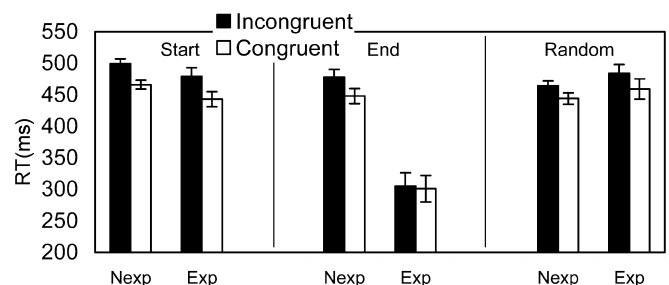

Fig. 3 Reaction time for partially explicit or nonexplicit participants (*NExp*) and complete explicit participants (*Exp*) split by congruency in the 5 initial sequence blocks (*Start*), in the 5 last sequence blocks (*End*) and in the final random block (*Random*)

sequence blocks, this effect disappeared for Exp participants but persisted in the case of NExp ones.

The ANOVA with the initial and final blocks separately confirmed this tendency. In the initial blocks, only the Congruency factor yielded a significant effect ($F(1,37) = 63.06$, $p < .001$). Differences between congruent and incongruent trials were 33 ms for NExp and 36 ms for Exp (see Fig. 3). For the 5 final blocks, the ANOVA also yielded a significant effect of Congruency ($F(1,37) = 15.55$, $p < 0.001$) and a significant Congruency $\times$ Knowledge interaction ($F(1,37) = 8.64$, $p < .01$). Differences between congruent and incongruent trials were 30 ms and 4 ms for NExp and Exp respectively. Thus, whereas NExp participants were affected by spatial compatibility during all the blocks, Exp participants were able to overcome the spatial interference in the last sequence blocks. The ANOVA with Type of Block (final sequence block and transfer-random one) showed significant effects of Type of Block ($F(1,37) = 59.26$, $p < .001$), Congruency ($F(1,37) = 20.27$, $p < .01$), and the triple Type of Block $\times$ Congruency $\times$ Knowledge interaction ($F(1,37) = 4.24$, $p < .05$). As Fig. 3 shows, whereas Congruency had no effect in the last sequence blocks for Exp participants, the effect of Congruency appeared again in the transfer-random block. Mean RT differences between congruent and incongruent trials were 20 and 25 ms for NExp and Exp participants respectively.

Discussion

As predicted, random physical location largely interfered with sequence learning. Only 34% of participants in the random symbolic condition (73% in the fixed symbolic condition and 100% in the spatial one) who received intentional instructions were able to learn and verbalize the sequence. Random symbolic participants with incidental instructions were completely unaware of the repeating sequence and did not show any RT change. Also confirming the prediction, explicit learners of both symbolic conditions (random and fixed) showed similar RTs in the last sequence blocks. Interestingly, the effect of congruency between letter and physical location was absent in the last 5 sequence blocks for Exp learners, whereas this effect persisted for NExp participants.

The lack of spatial interference for explicit learners can be clearly regarded as a response to some motor program or internal motor instructions (perhaps symbolically coded when symbols are involved). As has been proposed (Hoffmann & Koch, 1997; Nattkemper & Prinz, 1997), this kind of motor program enables response control to be taken independently from the stimuli. The formation of this knowledge structure could explain why learners from both symbolic conditions showed the same performance after some training blocks. Unlike in the Hoffmann and Koch experiment, however, the spatial condition always produced faster RTs than the symbolic ones. Therefore, our results

suggest that not all explicit learners were responding by means of the same mechanism. Spatial information was affecting positively the performance of both NExp and Exp spatial groups.

Hoffmann and Koch (1997) found similar RT patterns for explicit sequence learners when responses corresponded to either a sequence of symbols or a sequence of locations. Two principal experimental differences could account for such a discrepancy. First, their sequence involved four key-responses corresponding to either four locations (aligned horizontally) or four centered symbols. It is possible that spatial compatibility effects are stronger when only two locations (i.e., left and right) are involved. Also, the responses of their experiment required the use of the index and middle fingers of each hand (our experiment involved both index fingers only). Another important difference between the two experiments is the response-stimulus interval (RSI). In Hoffmann and Koch's experiment, the RSI was 500 ms whereas in our experiment it was 250 ms. It is possible that the additional 250 ms allowed explicit participants in Hoffmann and Koch's experiment to anticipate and prepare their next response, thus yielding faster RTs, especially when comparing the symbolic conditions.

The difference in RSI seems to be the best explanation for the RT difference between the Hoffmann and Koch symbolic condition and ours. In fact, recent experiments in our laboratory support this. Assuming that explicit symbolic learners were responding according to internal movement instructions, the time interval between the response and the next stimulus should be a determinant for an adequate sequencing of the responses. Symbolic motor programs that have been practiced in a few minutes (as is the case in our SRT experiment), and which are thus not completely automatic (Rosenbaum, Kenny, & Derr, 1983; Willingham, 1998), require some time for triggering each successive response. If we accept this assumption, we should also accept that our explicit spatial learners were not responding by means of the same mechanism as symbolic learners.

Our results suggest that both explicit and nonexplicit spatial learners were affected positively by spatial information. The difference between these groups (Exp and NExp) could be explained in terms of spatial memory efficiency or capacity. Better spatial memory may facilitate the translation from the spatial code to the verbal one. The results of Frensch and Miner (1994) are consistent with this hypothesis. They showed that spatial short-term memory capacity correlated with sequence learning under intentional conditions. Furthermore, learning in the intentional condition correlated with explicit knowledge. However, it could also be the case that Exp participants in the spatial condition were using, simultaneously, spatial and verbal (symbolic) codes. Although the present research cannot resolve this question, and bearing in mind individual differences, our data support two different learning mechanisms based on the different S-R links.

As we already mentioned, stimuli location automatically primes corresponding spatial responses (De Jong et al., 1994). Moreover, there is neuropsychological evidence of a direct link between eye movements and motor responses (Baker, Donoghue, & Sanes, 1999). This automatic link could explain why the spatial condition yielded faster RTs than the symbolic ones, regardless of the level of explicit knowledge; NExp participants assigned to the spatial condition responded faster than symbolic participants in both the Exp and NExp groups. The NExp spatial group also showed greater sequence learning than the NExp symbolic ones, suggesting that, similar to previous experiments (i.e., Mayr, 1996), spatial sequence learning was much less dependent on explicit knowledge. In this respect, only explicit participants in the symbolic conditions seemed to have clearly shifted the response control from the stimuli to internal movement instructions.

Furthermore, considering the existence of fast routes involving spatial codes, shifting from the spatial-fast route to the symbolic-slow one would have no benefit in the spatial condition. Accordingly, we hypothesize that whereas explicit symbolic learners based their responses on symbolically represented motor programs, both explicit and nonexplicit participants in the spatial condition were responding according to spatially represented motor programs. Learning by memorizing internal movement instructions would be especially necessary when slow, symbolic-based links have to be formed. Once the symbolic motor program has been formed, much more practice will be needed in order to respond as fast as the spatial routes allow.

The analyses of the "response repetition" effect were also consistent with this proposal. Participants in symbolic conditions responded faster to repetitions than to alternations in the random blocks[3] but they learned quickly the probabilistic structure of the response sequence: as alternations were much more frequent than repetitions, they were expecting a response alternation most of the time, yielding the observed inversion of the response repetition effect. However, explicit learners of both symbolic conditions overcome the "alternation" effect in the last sequence blocks: RTs were similar for both response repetitions and alternations. On the contrary, participants in the spatial condition always responded faster to alternations than to repetitions. Although this effect was weaker, explicit learners did not overcome it. One possible explanation for this difference could be related to the abstractness of the learned structure: whereas learners in the spatial condition were expecting an alternation most of the time, due to its higher probability, explicit learners in the symbolic conditions had parsed the sequence into the abstract pattern: double alternation and double repetition (see also Hoffmann & Koch, 1998 or Koch & Hoffmann,

2000b for a discussion of the parser process in sequence learning).

In conclusion, our results are consistent with those of Mayr (1996) and support the existence of two different sequence learning systems triggered by spatial and nonspatial stimulus attributes. However, our design did not allow a "pure" spatial mechanism related to the input system to be isolated, as far as spatial S-R correspondence was always present in the spatial condition. In our case, the observed learning mechanisms could be related to the slow and fast S-R links (De Jong et al., 1994). One of the mechanisms engaged in conditions of spatial S-R compatibility seems to produce learning, regardless of the verbal (explicit) knowledge, by means of the memorizing of a set of spatially-coded S-R links. The second mechanism, operating when nonspatial information is relevant, may depend on the memorizing of symbolically-coded movement instructions at least when symbols are involved. Zirngibl and Koch (2002) suggested the possibility that this kind of internal representation might take the form of R-R associations, but R-R chains had problems in representing serial order, especially for sequences where there are no unique associations, as stated in the well-known problem of serial order in memory and action (i.e., Lashley, 1951; Bower & Winzenz, 1969; Frensch, 1994; Koch & Hoffmann, 2000b). A higher-level structure seems to be necessary for representing temporal order information. If our symbolic explicit participants had parsed the sequence into the abstract pattern double repetition and double alternation (as suggested by some of the verbal reports), this structure could account for the absolute lack of spatial interference at the end of learning. Accordingly, control response might be based on the goal structure instead of the external stimulus. In this respect, we hope that future research will contribute to a better understanding of the role of symbolic representations or explicit knowledge in the development of abstract sequence structures or, as Hommel (2003) mentions, in the acquisition of plans for voluntary action.

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[3] This effect was only marginal in the first random block ($p = 0.08$), probably due to a longer RSI (250 ms) than that observed for the response repetition effect (50 ms).

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