Implicit visual learning: How the task set modulates learning by determining the stimulus–response binding

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Implicit learning is one of the most fundamental learning mechanisms that enables humans to adapt to regularities inherent in the environment. Despite its high flexibility, it depends on constraints, such as selective attention. Here, we focused on the stimulus-to-response binding which defines the dimensions of the stimuli and the responses participants attend to. In a serial reaction time task with a visual sequence, we investigated whether this stimulus–response binding influences the amount of sequence learning. The results of Experiments 1 and 2 showed that visual sequence learning is reduced when participants do not attend to the relevant response dimension. Furthermore, the findings of Experiment 3 suggest that attention to the relevant response dimension increased the development of explicit knowledge without affecting implicit knowledge. This latter finding is difficult to reconcile with the assumption that explicit learning results from the gradual strengthening of sequence representations.

1. Introduction

Implicit learning refers to the ability to adapt to regularities inherent in the environment in the absence of conscious awareness about the ongoing learning process itself or about the outcome of what is learned. This ability is fundamental for human beings as it allows us to act optimally in a rather stable environment without any additional effort.

One of the most frequently utilized paradigms in the field of implicit learning is the serial reaction time task (SRTT) originating from Nissen and Bullemer (1987). In this standard SRTT, participants see locations on the screen which are mapped to spatially corresponding keys. Participants are instructed to press the appropriate response key whenever an asterisk occurs at a certain location. Unbeknownst to the participants, the locations of the asterisk follow a regular sequence. After several blocks of practice, participants are transferred either to a new, but also regular sequence or to a random sequence. This transfer block leads to a performance decrement that disappears almost immediately when the original regularity is reintroduced. Importantly, participants are not able to explicate their acquired knowledge when asked to do so. Even with more sensitive tests including the recently introduced wagering task (Dienes & Seth, 2010; Haider, Eichler, & Lange, 2011; Persaud, McLeod, & Cowey, 2007) or the process-dissociation procedure (Destrebecqz & Cleeremans, 2001; Haider et al., 2011; Jacoby, 1991), explicit knowledge of the sequence is rare. This dissociation between performance and expressible knowledge is generally assumed to indicate implicit learning.

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Former research with the SRTT has focused heavily on motor sequences; that is, the responses almost always followed a regular sequence. Consequently, many findings have suggested that learning in the SRTT is based on stimulus–response learning or learning of response locations (e.g., Willingham, 1998; Willingham, 1999; Willingham, Nissen, & Bullemer, 1989; Willingham, Wells, Farrell, & Stemwedel, 2000). More recent findings with the SRTT have revealed, however, that the characteristics of the sequence determine what is learned (e.g., Abrahamse, Van der Lubbe, & Verwey, 2008; Deroost & Soetens, 2006a; Deroost & Soetens, 2006b; Goschke & Bolte, 2007; Goschke & Bolte, 2012; Haider, Eberhardt, Kunde, & Rose, 2012; Mayr, 1996; Remillard, 2003; Remillard, 2011; Richard, Clegg, & Seger, 2009; Rose, Haider, Saliari, & Büchel, 2011; for a review, see Abrahamse, Jiménez, Verwey, & Clegg, 2010). Even if only the stimuli follow a regular sequence while responses are randomly mapped to stimuli, implicit learning is found (e.g., Cheyse, Gevers, De Shutter, Van Waelvelde, & Fias, 2009; Goschke & Bolte, 2012; Haider et al., 2012; Rose et al., 2011). Thus, implicit learning is highly flexible. It does not refer to one single learning mechanism. Rather, whenever a regular sequence is built into the task, it is learned irrespective of whether it consists of stimulus–stimulus, response–stimulus, response–response, or response–effect associations (e.g., Frensch, 1998; Haider et al., 2012; Whittlesea & Dorken, 1993).

In spite of this high flexibility of implicit learning, some constraints exist that determine whether or not a certain sequence is learned. These constraints can best be described with reference to research on action control; that is, in terms of a task set. A task set refers to a given stimulus, the response to that stimulus, and the nature of their mapping (e.g., Allport, Styles, & Hsieh, 1994). More precisely, the task set defines the stimulus-to-response (S–R) binding, that is, which particular dimensions of the stimulus are bound to which dimensions of the response.

If, for example, the location of a stimulus is the relevant dimension for the task at hand, then the location of the stimulus should be part of the current S–R binding. By contrast, if participants are asked to respond to the identity of the stimulus (i.e., its color, its shape, etc.) they might represent color or shape in the S–R binding. Thus, the function of the task set is to define the dimension of the stimulus to which a participant selectively attends (see, e.g., Cock, Berry, & Buchner, 2002; Deroost, Zeischka, & Soetens, 2008; Etam, Schul, & Hassin, 2009; Jiang & Chun, 2001; Jiménez, 2003; Jiménez & Méndez, 1999; Jiménez & Méndez, 2001; Jiménez, Vaquero, & Lupiáñez, 2006; Jiménez & Vázquez, 2005; Jiménez & Vázquez, 2011; Tanaka, Kiyokawa, Yamada, Diener, & Shigemasu, 2008).

The same is also true for the response dimension. Recently, Gaschler, Frensch, Cohen, and Wenke (2012) provided evidence that instructions can determine which dimensions of the stimulus and the responses a participant attends to. In their experiments, participants received either a color instruction (to press the red, blue, yellow, or green key) or a spatial instruction (to press the outer or inner left/right key). Importantly, in both conditions participants received the identical sequence. Nevertheless, they learned the color sequence in the color instruction condition and the spatial sequence in the spatial instruction condition. Thus, besides selective attention to stimuli, the task set which controls for response selection – through, for example, the instruction – also influences the content of implicit learning (e.g., Gaschler et al., 2012; Hommel, 2004; Kiesel et al., 2010; Wenke et al., 2007; Willingham et al., 2000; Ziessler, 1994; Ziessler, 1998; Ziessler, Nattkemper, & Frensch, 2004).

In addition, some researchers have shown that differences in how responses are produced affected the amount of learning within a SRTT (e.g., Haider et al., 2012; Richard et al., 2009; Zirngibl & Koch, 2002). For instance, Richard et al. (2009) found evidence that participants only learned a regular sequence of target movements when they were instructed to respond with one single finger. By contrast, no such learning was found when participants responded with keys mapped to the respective endpoint of the movement. In terms of S–R binding, in the former case, the movement of the stimulus is bound to the movement of the finger whereas it is bound to the key-location in the latter case. Thus, the S–R binding differs between conditions and only participants in the movement condition represent the movement of the finger as the current response.

In a similar vein, Haider et al. (2012; see also Rose et al., 2011) trained participants with either a pure motor (R–R) or pure visual (S–S) sequence. In their picture-matching SRTT, six response squares were presented on the screen with each containing a different color. Then a target stimulus occurred and participants had to respond to the response square containing this target color. Arrangement of colors to the response squares changed from trial to trial and consequently the stimulus-to-response mapping also changed from trial to trial. Therefore, either only the target stimuli (pure visual sequence) or only the responses could follow a regular sequence (pure motor sequence; see, Fig. 1, Panel A). If participants responded by key-presses they showed reduced learning of the visual sequence as compared to the motor sequence. However, if, in a second condition, participants responded by moving a mouse toward the response squares depicted on the screen, they acquired the same amount of knowledge for both the visual and the motor sequence. Haider et al. (2012) also explained their results in terms of differences in the S–R bindings. In the keyboard condition, participants probably represent the response key locations in their S–R binding. By contrast, in the mouse condition, the action goal is to move the mouse to a response square which contains a particular color and is located at a certain screen position. Hence, they should represent color and location in their S–R bindings.

To summarize, there is evidence that implicit learning in the SRTT depends not only on the specific characteristics of the sequence built into the task, but also on the particular task set. The content of the task set, or more precisely, the S–R binding, is determined by the specific characteristic of the experimental set-up (e.g., the instruction, the response device, etc.), and, as such directs attention to certain stimulus and response dimensions which, in turn, determines whether sequences built into the task are learned.
2. Purpose of the experiments

The three experiments reported here further investigated the influence of differences in the S–R binding on the amount of learning within a SRTT. In particular, we focused on the role of attention to response dimensions. For this purpose, we trained participants with the above mentioned picture-matching SRTT of Rose et al. (2011) and Haider et al. (2012). Again, participants responded either with the keyboard or with the mouse.

The goal of the three experiments reported here was threefold: The goal of Experiment 1 was to replicate the Haider et al.'s (2012) finding of a reduced visual sequence learning effect in the keyboard, but not in the mouse condition. Experiment 2 focused more stringently on the role of the S–R binding by increasing the distinctiveness of the response dimensions. This was achieved by presenting redundant tones associated with either the pattern (augmenting the visual sequence by a regular tone sequence) or the location of the response squares (leading to a random sequence of the tones, cf. Hoffmann, Sebald, & Stöcker, 2001). Experiment 3 then investigated whether the response device manipulation affected the acquisition of implicit or explicit knowledge.

One general problem concerning the comparison of visual and motor sequence learning needs some further discussion. As argued by Koch and Hoffmann (2000), implicit visual and motor sequence learning introduces a major confound as these two kinds of sequences additionally differ on the spatial dimension. Whereas a visual sequence does not necessarily contain spatial information, a motor sequence does. Consequently, implicit motor learning automatically primes the next response. In contrast, implicit visual learning only leads to faster encoding of the next stimulus when, as it is the case in the current experiments, stimuli and response locations are randomly mapped (Haider et al., 2012). These confounds might contribute to differences in learning or to differences in the expression of learning. Hence, findings of more pronounced motor learning effects when assessed by response time measures (e.g., Gheysen et al., 2009) are ambiguous. Therefore, the goal of the current experiments made it necessary to use a knowledge test after training. Such an off-line test provides a fairer picture about the degree to which associations between successive elements of the sequence have been learned.

At least in the field of SRTT learning, measuring implicit learning in a sequence knowledge test but not in performance measures sounds counterintuitive, as many researchers in this field assume that such direct knowledge tests mainly reflect explicit knowledge. However, as argued by, for example, Dienes and Perner (1999; see also, Dienes & Seth, 2010; Haider & Frensch, 2005; Haider & Frensch, 2009; Haider et al., 2011; Lau & Rosenthal, 2011; Rünger & Frensch, 2010; Seth et al., 2008) explicit
knowledge refers to knowledge for which a participant knows that he/she possesses it. This does not necessarily have to be the case when participants produce the correct sequence (or parts of the sequence) in post-experimental knowledge tests.

Persaud et al.’s (2007) wagering task, that we adopted here, is well suited to assess whether a participant knows that he/she knows about the sequence (i.e., has explicit knowledge) or whether he/she does not but still produces knowledge well above chance level (i.e., has implicit knowledge). This wagering task is a variant of the generation task originated by Nissen and Bullemer (1987). Both tasks are almost entirely identical to the training phase of the SRTT. The only difference between training and test phases is that in some trials a question mark instead of the target stimulus occurs. In these trials, participants must generate a response on their own. In the wagering task, they are subsequently also asked to place a wager on the correctness of their response (see, Fig. 1, Panel B).

These wagers are highly informative about the assessment of implicit and explicit knowledge. Participants can be said to possess explicit knowledge when they place more high than low wagers after having responded correctly. By contrast, participants who only acquired implicit knowledge should not know that they have any knowledge. Consequently, they should not be able to place high wagers when responding correctly (the zero-correlation criterion of unconscious knowledge, Dienes, Altmann, Kwan, & Goode, 1995) even though their sequence knowledge should exceed chance level (for an extensive validation of this wagering task, see Haider et al., 2011).

3. Experiment 1

The purpose of Experiment 1 was to replicate the finding of Haider et al. (2012) that the response device manipulation (keyboard vs. mouse) affected implicit visual sequence learning but not implicit motor sequence learning. We also investigated the role of verbal representations in visual implicit learning. Previous experiments that have revealed implicit visual learning all used easy-to-name color stimuli (Gheysen, Van Opstal, Roggeman, Van Waeselde, & Fias, 2010; Gheysen, Van Opstal, Roggeman, Van Waeselde, & Fias, 2011; Gheysen et al., 2009; Haider et al., 2012; Rose et al., 2011). Consequently, it might be that the visual learning effects result from naming the stimuli and thus from the generation of verbal representations that then were associated over time.

The experimental design was identical to that used in Haider et al.’s (2012) Experiment 2 with the exception that abstract, hard-to-name stimuli were used (see, Fig. 1; Panel C). As in the original experiment, we compared the amount of acquired knowledge of participants in the Mouse and the Keyboard condition who received either a motor or a visual sequence. If visual implicit learning does not require the generation of verbal representations we should be able to replicate the basic findings: Participants in the keyboard condition should show reduced visual sequence knowledge compared to motor sequence knowledge in the motor sequence condition. By contrast, participants in the two mouse conditions should produce equal amounts of visual and motor sequence knowledge.

3.1. Method

3.1.1. Participants

One hundred twenty-two students (35 men) of the University of Cologne participated in the experiment. Mean age of participants was 21.1 (SD = 2.21). No participant reported color-blindness. Participants received either course credit or €5 for participation. In addition, they could earn some extra money in the wagering task. Participants were randomly assigned to one of the following four conditions: Mouse-visual condition, Keyboard-visual condition, Mouse-motor condition, or Keyboard-motor condition.

3.1.2. Materials

Six square, abstract patterns served as the stimuli. They were easily distinguishable from each other but hard to verbalize because they did not depict any concrete objects or shapes (see Fig. 1, Panel C). For all participants, one stimulus formed the target in each trial. It appeared in the center of the upper third of the screen (see Fig. 1, Panel A). Below, six response squares containing the different patterns were shown. In the two visual sequence conditions, the six different targets followed a 6-elements first-order sequence while locations of the response square containing the target pattern were randomly mapped to the stimuli. In the two motor sequence conditions, the same six targets were randomly presented, but the locations of the response square containing the target pattern followed a regular sequence. In the two Mouse conditions, participants were instructed to move the mouse to the response square containing the target pattern and to click on it (RT was measured from target-onset until the mouse-click on the respective response square occurred). In the Keyboard conditions, each response square position was assigned to one specific response key (Y, X, C, B, N, and M on a regular QWERTZ keyboard). The participants’ task was to press the key assigned to the location of the square containing the pattern of the target. In both the Mouse and the Keyboard conditions, the pattern of the response squares changed from trial to trial such that responses were completely disentangled from the visual pattern sequence.

To assess participants’ knowledge, the wagering task was used (Haider et al., 2011). This task was identical to the training blocks but contained overall 36 wager trials. In these wager trials, a question mark occurred instead of a target pattern (see Fig. 1, Panel B). Participants were asked to predict the pattern (visual sequence condition) or the location (motor sequence condition) of the next response. Subsequently, they had to place a wager (either 1 Cent or 50 Cents) on the correctness of their response.
3.1.3. Procedure

For all participants, the experiment started with computer presented instructions. Participants were informed about the task and received 20 test-trials in order to familiarize them with the task. Then, 10 training blocks were given, containing 90 trials each. For each participant and each block, the visual target sequence (visual sequence) or the sequence of response square locations (motor sequence) started at a randomly determined position.

During training, each trial began with the presentation of the response squares. One hundred milliseconds after their occurrence, the target appeared. Whereas the target disappeared after 150 ms, the response squares remained on the screen until the participant responded either by clicking on a response square (Mouse condition) or by pressing the key assigned to the location of the response square (Keyboard condition). After the participant’s response, the screen went black for 300 ms. Then the next trial started with the presentation of the six response squares showing the patterns in a different order. Incorrect responses were signaled by a 400 Hz tone lasting 50 ms. At the end of each training block, participants received feedback about their average speed and error rate. They were allowed to take a short break after each block. Immediately after the tenth training block, the wagering task began.

The wagering task also started with computer presented instructions. Participants were told that they would sometimes see a question mark instead of the target pattern. It was further explained to them that when they saw the question mark, they should predict the pattern of the next response square and subsequently should place their wager (either 1 or 50 Cent) on the correctness of their guess. Participants were also informed about the existence of a regular sequence before the wagering task started. However, they did not receive any further information about the sequence; that is, they were not informed about the existence of a visual or response sequence, about its length, or any other characteristic.

Participants in the Mouse and the Keyboard conditions used the same response device they had used in the training blocks. In 36 of the overall 170 trials, a question mark occurred instead of the target pattern. All six patterns were equally often replaced by this question mark. The pattern of the response squares did not change order in these wagering trials because participants, particularly in the Keyboard conditions, might remember the location of their last response square (but not the last pattern) and attend to this position in order to predict the next pattern. Therefore, changing the pattern of the response squares from trial to trial, as we did in all remaining trials, might overwrite the representation of the last response pattern. This would be especially detrimental in the visual conditions in which the task was to predict the next response pattern, requiring participants’ knowledge of the last seen response pattern.

In the wagering trials, participants guessed the pattern of the next response square (visual sequence condition) or of the next response location (motor sequence condition) either by clicking on the respective response square (Mouse condition) or by pressing the respective key (Keyboard condition). Subsequently, a 1 Cent and a 50 Cent button appeared on the screen and participants either had to click on one of these buttons (Mouse condition), or to press the “a”-key for a 1 Cent wager or the “k”-key for a 50 Cent wager (Keyboard condition). If a participant’s answer was correct, she/he won the amount of their wager; if not, she/he lost it. Participants were free to use low and high wagers as frequently as they pleased and in such a way as to maximize their earnings. After every 54 trials (containing 12 wager trials; 62 trials in Block 1), participants received feedback about how much they had earned (that is, overall 3 times). The maximum that could be earned was set to 8€. If a participant reached this maximum before the end of the third block, the wagering task was terminated at the ending of the current block. After the wagering task, all participants were interviewed about their knowledge. Finally, they received the total amount of money they had earned in the wagering task and were then debriefed.

3.2. Results and discussion

We first analyzed participants’ mean error rates per block in the SRTT. Participants were excluded from further analysis if they had made more than 15% errors in each of the 10 training blocks. Six participants in the Keyboard-motor, one in the Keyboard-visual, and two in the Mouse-visual conditions were excluded from further data analyses. This left 30 participants in the Mouse-visual and in the Mouse-motor conditions respectively, 24 in the Keyboard-visual and 29 in the Keyboard-motor conditions.

Because we were mainly interested in the amount of acquired knowledge, we first discuss the findings concerning participants’ sequence knowledge in the wagering task. We then report the results for error rates and latencies in the training task.

3.2.1. Knowledge in the wagering task

The findings of the wagering task are depicted in Table 1. The first column presents the mean percent of correct responses. The next two columns show the mean percent correct responses when participants placed a high wager (second column), or when they placed a low wager (third column). As can be seen, participants of all conditions had more than chance-level sequence knowledge (chance level was .20; all ts > 3.06, ps < .05).

A 2 (Response Device: Mouse vs. Keyboard) × 2 (Sequence: visual vs. motor sequence) ANOVA with mean percent correct responses as the dependent variable yielded only a significant interaction between Response Device and Sequence ($F(1,109) = 6.87, MSe = .084, p < .01, \eta^2_g = .06$). This was due to the two Keyboard conditions. Participants here had significantly less knowledge about the visual than the motor sequence ($F(1,109) = 7.87, MSe = .084, p < .01, \eta^2_g = .07$). By contrast, participants in the two Mouse conditions showed rather identical amounts of knowledge about the visual and the motor sequences ($F < 1$). Furthermore, participants in the Mouse and Keyboard motor conditions did not differ in their amounts
of motor sequence knowledge ($F < 1$). This latter finding is important as it argues against the possibility that the knowledge difference found for the visual sequence was due to differences in memory load between the Mouse and the Keyboard conditions (Lavie, 2005).

We next investigated whether participants’ knowledge in the Mouse and the Keyboard conditions was implicit or explicit. For this purpose, we analyzed participants’ percent correct responses when they had either placed high or low wagers. According to the zero-correlation criterion of Dienes and Seth (2010), implicit knowledge can be inferred when the number of correct responses under high wagers is equal to or less than the number of correct responses under low wagers. By contrast, having more correct responses with high than low wagers indicates explicit knowledge (see Haider et al., 2011).

The results depicted in Table 1 suggest that all participants have acquired some explicit knowledge as their rate of correct responses was higher for high wagers than for low wagers. A 2 (Response Device) × 2 (Sequence) × 2 (Wager: high vs. low) ANOVA with percent correct responses as dependent variable yielded a significant main effect of Wager, $F(1,109) = 40.47$, $MSE = 0.07$, $p < .01$, $\eta^2_g = 0.27$, as well as a significant three-way interaction between Response Device, Sequence, and Wager ($F(1,109) = 5.07$, $MSE = 0.07$, $p < .05$, $\eta^2_g = 0.04$). This three-way interaction revealed once again that, in line with the findings of Haider et al. (2012), participants in the Keyboard-visual condition had less explicit knowledge than those in the other three conditions.

To further clarify the impact of our response device manipulation on the acquisition of explicit knowledge, we additionally identified participants with entirely explicit knowledge. As Haider et al. (2011) have shown, only participants who have acquired explicit knowledge during training (indicated by abruptly occurring RT-decreases) are able to place high wagers right from the beginning of the wagering task when responding correctly and also reach the maximum of earnings before the end of the wagering task.

Overall, 28 participants reached the maximum of earnings before or at the end of the third block of the wagering task (and thus had acquired explicit knowledge about the entire sequence); 9 in the Mouse-visual condition, 7 in the Mouse-motor and 11 in the Keyboard-motor conditions. Only one participant in the Keyboard-visual condition acquired entirely explicit knowledge. For means of illustration, Fig. 2 depicts the earnings per block of the wagering task separately for participants with entirely explicit knowledge and the remaining participants (with implicit knowledge). As can be seen, even in the first block the earnings of these participants are much higher than those of the remaining participants. In addition, Fig. 2 also shows that the remaining participants did not learn anything about the sequence during the wagering task as they did not show any increase in their earnings.

A Fisher’s exact test confirmed that the number of participants with entirely explicit knowledge was significantly higher in the Keyboard-motor than in the Keyboard-visual conditions ($\chi^2(1) = 8.55$, $p < .01$). For means of comparison the difference between the two Mouse conditions did not reach significance ($\chi^2(1) < 1$).

Overall, the knowledge data analysis replicated Haider et al.’s (2012) main finding that participants in the Keyboard visual condition had acquired less knowledge than participants in the remaining ones. In order to directly compare the Haider et al.’s results with the current findings, we conducted two additional ANOVAs that pitted their study against the current one by including experiment as a factor. Neither the first 2 (Experiment) × 2 (Response Device) × 2 (Sequence) ANOVA nor the second 2 (Experiment) × 2 (Response Device) × 2 (Sequence) × 2 (Wager) ANOVA yielded any significant effect of the Experiment factor ($F_s < 2$, $p_s > .15$). Hence, the current findings with hard-to-name abstract pictures exactly replicated Haider et al.’s (2012) results with easy-to-name pictures.

The finding that some participants acquired entirely explicit knowledge even with a hard-to-name visual sequence suggests that the emergence of an explicit representation of the entire sequence does not require verbal representations. This was also confirmed by the post-experimental interviews. Participants in the visual sequence conditions with entirely explicit knowledge were able to state that there was a sequence during training, but were unable to name the pictures when asked to do so. However, they produced the correct sequence when instructed to arrange the pictures in sequential order.

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1 The Response device × Sequence ANOVA partly overlaps with the Response device × Sequence × Wager ANOVA. We report both analyses mainly because the two measures slightly differ due to different denominators. Overall percent correct refers to the relative amount of correct trials and thus reflects an exact measure of participants’ overall sequence knowledge. Percent correct responses under the condition of high (low) wagers refer to a different denominator (the amount of trials with high [low] wagers). However, we restrict the report of the second ANOVA to only the Wager effects.
3.2.2. Error rates and Latencies in the Training Blocks

The mean error rates ranged between 1.22% and 8.58% (see Table 2). Participants in the two Keyboard conditions made more errors than those in the two Mouse conditions. Furthermore, mean error rates in all conditions first decrease and then slightly increased at the end of training.

A 2 (Response Device: Mouse vs. Keyboard) × 2 (Sequence: visual vs. motor) × 10 (Practice Block) ANOVA with mean error rates as dependent variable yielded a significant main effect of Response device ($F(1,109) = 44.0, MSe = 0.008, p < .01, \eta^2_p = 0.29$). In addition, the main effect of practice ($F(9,981) = 5.69, MSe = 0.001, p < .01, \eta^2_p = 0.05$) was significant as well as the two-way interaction between Response device and practice ($F(9,981) = 1.97, MSe = 0.001, p < .05, \eta^2_p = 0.02$) and the three-way interaction between Response device, sequence, and practice ($F(9,981) = 2.49, MSe = 0.001, p < .01, \eta^2_p = 0.02$). The three-way interaction was due to participants in the Mouse-motor condition making more errors than the Mouse-visual condition, while in the Keyboard condition the pattern was reversed; that is, more errors in the Keyboard-visual condition than in the Keyboard-motor condition. These differences across conditions slightly increased at the end of training.

Fig. 3 represents the means of median RTs for the four conditions. A 2 (Response Device) × 2 (Sequence: visual vs. motor) × 10 (Practice Block) ANOVA with median RT as dependent variable revealed significant (main effects of Response device ($F(1,109) = 6.16, MSe = 214,188.3, p < .05, \eta^2_p = 0.26$), of sequence ($F(1,109) = 38.40, MSe = 214,188.3, p < .01, \eta^2_p = 0.26$), and of practice ($F(9,981) = 120.11, MSe = 9532.3, p < .01, \eta^2_p = 0.52$). In addition, the two-way interaction between Response device and practice was significant ($F(9,981) = 3.43, MSe = 9532.2, p < .01, \eta^2_p = 0.03$), as was the sequence by practice interaction ($F(9,981) = 15.24, MSe = 9532.2, p < .01, \eta^2_p = 0.12$). The former interaction indicated that participants in the two Keyboard conditions were slower than those in the two Mouse conditions at the beginning of practice, but not at the end. The latter interaction was due to the greater acceleration in the two motor sequence conditions than in the two visual sequence conditions.

Thus, in line with the results of Haider et al. (2012; see, also Gheysen et al., 2009; Rose et al., 2011), the training performance analysis suggests more pronounced practice effects in the motor sequence conditions than in the visual sequence conditions. However, as revealed by the knowledge data, this difference was not due to more learning in the two motor-conditions (at least in the Mouse conditions). Rather, in our experimental set-up, knowledge about a motor sequence can help speed up responses by anticipatory response preparation while visual sequence knowledge mainly enhances encoding processes which do not have a profound effect on response times.

### Table 2

Percent error rate and standard deviations (in parentheses) as a function of training block and condition in the training phase of Experiment 1.

<table>
<thead>
<tr>
<th>Practice Block</th>
<th>Condition</th>
<th>Mouse visual</th>
<th>Mouse motor</th>
<th>Keyboard visual</th>
<th>Keyboard motor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block 1</td>
<td>Mouse visual</td>
<td>3.90 (4.13)</td>
<td>3.11 (2.55)</td>
<td>7.59 (3.69)</td>
<td>8.58 (5.43)</td>
</tr>
<tr>
<td>Block 2</td>
<td>Mouse visual</td>
<td>2.07 (2.24)</td>
<td>2.19 (2.68)</td>
<td>6.76 (4.43)</td>
<td>5.87 (2.77)</td>
</tr>
<tr>
<td>Block 3</td>
<td>Mouse visual</td>
<td>1.78 (2.25)</td>
<td>1.86 (2.05)</td>
<td>6.76 (3.57)</td>
<td>4.95 (3.80)</td>
</tr>
<tr>
<td>Block 4</td>
<td>Mouse visual</td>
<td>1.41 (1.60)</td>
<td>1.52 (2.25)</td>
<td>5.60 (3.63)</td>
<td>5.78 (3.12)</td>
</tr>
<tr>
<td>Block 5</td>
<td>Mouse visual</td>
<td>1.59 (1.51)</td>
<td>2.00 (2.25)</td>
<td>4.32 (3.23)</td>
<td>4.87 (3.38)</td>
</tr>
<tr>
<td>Block 6</td>
<td>Mouse visual</td>
<td>1.48 (2.79)</td>
<td>2.89 (6.71)</td>
<td>4.49 (4.63)</td>
<td>6.48 (7.41)</td>
</tr>
<tr>
<td>Block 7</td>
<td>Mouse visual</td>
<td>1.22 (1.69)</td>
<td>1.59 (2.49)</td>
<td>5.23 (4.74)</td>
<td>4.18 (2.94)</td>
</tr>
<tr>
<td>Block 8</td>
<td>Mouse visual</td>
<td>1.37 (1.64)</td>
<td>3.93 (8.31)</td>
<td>5.23 (6.79)</td>
<td>3.76 (2.49)</td>
</tr>
<tr>
<td>Block 9</td>
<td>Mouse visual</td>
<td>1.22 (1.69)</td>
<td>1.93 (2.44)</td>
<td>7.69 (11.95)</td>
<td>4.76 (4.50)</td>
</tr>
<tr>
<td>Block 10</td>
<td>Mouse visual</td>
<td>1.52 (1.74)</td>
<td>2.44 (3.79)</td>
<td>6.39 (9.58)</td>
<td>3.41 (3.23)</td>
</tr>
</tbody>
</table>
To summarize, Experiment 1 replicated the findings of Haider et al. (2012). That is, participants in the Keyboard-visual condition expressed less knowledge than participants in the Keyboard-motor condition, whereas participants of the two Mouse conditions did not show this detrimental effect for the visual sequence. This nicely fits our assumption that the S–R binding in the Keyboard-visual and the Mouse-visual conditions do differ. In the former condition, participants mainly attended to the key location which was assigned to the position of the response square announced by the target. Thus, they might have encoded the location of the response squares in the S–R binding rather than the picture of the response square. By contrast, in the Mouse condition response selection is controlled by the pattern and the location of the response squares. This, in turn, leads to the representation of the location and the picture of the response squares in the S–R binding. Experiment 2 was aimed to further investigate this conclusion.

Furthermore, because we used abstract and hard-to-name stimuli here, our replication of Haider et al.’s (2012) results suggests that visual learning merely affects encoding processes. It does not seem to be established via verbal representations leading to internal verbal responses (Rose et al., 2011). Surprisingly, even the acquisition of explicit knowledge about the entire sequence seems to require no verbal representations. Rather, our results suggest that a stable perceptual representation is sufficient to integrate single associations into a representation of the entire sequence. Thus, contrary to Rünger and Frensch (2010) who argued that verbal reports are the best indicator for explicit knowledge, our results suggest that participants had explicit knowledge, even when they were not able to verbally describe the sequence. This knowledge could be revealed in the wagering task which is based on the strategic use of knowledge rather than on reportability of the sequence.

4. Experiment 2

The goal of Experiment 2 was to more directly test the assumption that participants in the visual Keyboard condition, when responding to the target, attend less to the identity of the pattern in the response square than participants in the Mouse condition. For this purpose, all participants received a visual sequence together with contingent tones that were either mapped to the identity of the stimulus (i.e., response to Picture 1 – Tone 1, to Picture 2 – Tone 2, etc.) or to location of the response squares (i.e., response to Location 1 – Tone 1, to Location 2 – Tone 2, etc.). The tones were always presented directly after participants’ response. As only the stimuli followed a regular visual sequence, the picture-tone associations led to a repeating melody whereas the response location-tone associations did not.

If the assumption is correct that the S–R binding in the Keyboard condition does not include the stimulus-pattern, we should not find any benefit from tones associated to the pattern of the stimulus compared to tones associated to response locations. By contrast, in the Mouse condition, we expected to find more sequence knowledge when the tones were associated to the pictures than when they were associated to the response location.

4.1. Method

4.1.1. Participants

Ninety-six students (36 men) of the University of Cologne participated in the experiment. Mean age of participants in the experimental condition was $M = 21.7$ (SD = 3.4). None of the participants had participated in previous SRTT-experiments, and no one reported being color-blind. As in Experiment 1, students received either course credit or €5 for participation and could
earn some extra money in the wagering task. Participants were randomly assigned to either the Mouse-PT (picture-tone), the Mouse-RLT (response location-tone), the Keyboard-PT, or the Keyboard-RLT conditions.

4.1.2. Materials and Procedure

Material and procedure were identical to the visual conditions of Experiment 1. The only difference was that for half of the participants, six different tones were associated to the pictures of the stimuli whereas they were associated to the response locations for the other half of participants. In both cases, the tones immediately followed the response (the mouse click or the key-press). In the wagering task, no tones were presented.

4.2. Results and discussion

As we did for Experiment 1, we first analyzed participants’ error rates. Ten participants exceeded our error criterion of 15% errors per block. In addition, due to wrong key usage in the wagering task, data of three additional participants had to be excluded. The final sample sizes were 20 participants in the Mouse picture-tone (Mouse-PT), 20 in the Mouse response location-tone (Mouse-RLT), 26 in the Keyboard-PT, and 17 in the Keyboard-RLT conditions. For these participants, we first report the results of the wagering task and then the mean error rates and median response times for training blocks.

4.2.1. Knowledge in the wagering task

The results of the wagering task are depicted in Table 3. It may be seen that participants in all four conditions had more than chance-level knowledge (all ts > 4.4, all ps < .05).

A 2 (Response Device) × 2 (Tone: PT vs. RLT) ANOVA with overall percent correct responses as the dependent variable yielded significant main effects of Response Device \( F(1,79) = 19.45, \ MSe = 0.081, p < .01, \ \eta_p^2 = 0.20 \text{ and of Tone} \ (F(1,79) = 10.33; \ MSe = 0.081, p < .01, \ \eta_p^2 = 0.12) \text{. The interaction was not significant } (F(1,79) = 2.01, \ MSe = 0.081, p = .1598, \ \eta_p^2 = 0.02) \text{.}

Thus, participants in the two Mouse conditions expressed significantly more knowledge than participants in the two Key- board conditions. Furthermore, the tones associated with the stimuli increased knowledge in the Mouse and the Keyboard conditions.

The second 2 (Response Device) × 2 (Tone) × 2 (Wager) ANOVA examined the percent of correct responses when participants placed high or low wagers. This ANOVA revealed a significant main effect of Wager \( (F(1,79) = 44.67, MSe = 0.067, p < .01, \ \eta_p^2 = 0.36) \text{. The effect was qualified by a significant Response Device by Wager interaction } (F(1,79) = 12.22, \ MSe = 0.067, p < .01, \ \eta_p^2 = 0.13) \text{, and a significant three-way interaction between Response Device, Tone, and Wager } (F(1,79) = 4.22, \ MSe = 0.067, p < .05, \ \eta_p^2 = 0.05) \text{. This three-way interaction confirmed that the tones associated with the picture enhanced the acquisition of explicit visual sequence knowledge in the Mouse-PT condition, but not in the Keyboard-PT condition. Accordingly, separately conducted interaction contrasts } (\text{Tone × Wager}) \text{ showed that participants in the Mouse-PT condition had significantly more explicit knowledge than those in the Mouse-RLT condition } (F(1,79) = 9.92, \ MSe = .067, p < .01, \ \eta_p^2 = 0.11) \text{. By contrast, this interaction was not significant in the Keyboard conditions } (F < 1) \text{.}

As in Experiment 1, we identified those participants who had – according to our criterion of earnings – acquired entirely explicit knowledge during training. Overall, we identified 25 such participants, 14 participants in the Mouse-PT, six in the Mouse-RLT, four in the Keyboard-PT, and one participant in the Keyboard-RLT conditions. The number of participants with entirely explicit knowledge in the Mouse-PT condition was significantly higher than in the Mouse-RLT condition \( (\chi^2(1) = 6.4, p = .05) \text{, whereas the two Keyboard conditions did not differ } (\chi^2(1) < 1) \text{. Thus, only participants in the Mouse-PT condition benefited from the contingent stimulus-tone association even though participants in the Keyboard-PT condition also heard a repeating melody during training due to the visual sequence. This solidifies our assumption that participants in the keyboard conditions did attend less to the pattern of the stimuli while generating their responses.}

4.2.2. Error rates and latencies in the training blocks

Error rates for participants ranged between 1.1% and 13.0% (see Table 4). A 2 (Response Device) × 2 (Tone) × 10 (Practice Block) ANOVA with error rates as the dependent variable yielded significant main effects of Response Device \( (F(1,79) = 65.24, \ MSe = .0053, p < .01, \ \eta_p^2 = 0.45) \text{ and Practice Block } (F(9,711) = 10.29, \ MSe = .0009, p < .01, \ \eta_p^2 = 0.11) \text{. These main effects were qualified by a significant two-way interaction between Response Device and Practice Block } (F(9,711) = 5.22, \ MSe = .0009, p < .01, \ \eta_p^2 = 0.06) \text{ as well as a significant three-way interaction } (F(9,711) = 2.16, \ p < .05) \text{. The two Keyboard conditions did not differ } (\chi^2(1) < 1) \text{. Thus, only participants in the Mouse-PT condition benefited from the contingent stimulus-tone association even though participants in the Keyboard-PT condition also heard a repeating melody during training due to the visual sequence. This solidifies our assumption that participants in the keyboard conditions did attend less to the pattern of the stimuli while generating their responses.}

Table 3

<table>
<thead>
<tr>
<th>Condition</th>
<th>Percent correct</th>
<th>High wager</th>
<th>Low wager</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mouse PT</td>
<td>76.39 (29.5)</td>
<td>80.29 (26.4)</td>
<td>20.61 (29.4)</td>
<td>20</td>
</tr>
<tr>
<td>Mouse RLT</td>
<td>47.15 (36.2)</td>
<td>50.08 (36.8)</td>
<td>26.89 (31.4)</td>
<td>20</td>
</tr>
<tr>
<td>Keyboard PT</td>
<td>39.60 (28.9)</td>
<td>39.98 (28.1)</td>
<td>25.48 (21.5)</td>
<td>26</td>
</tr>
<tr>
<td>Keyboard RLT</td>
<td>28.27 (18.7)</td>
<td>28.37 (20.9)</td>
<td>16.92 (14.4)</td>
<td>17</td>
</tr>
</tbody>
</table>
MSe = .0009, \( p < .05, \eta_p^2 = 0.03 \). As in Experiment 1, participants in the two Keyboard conditions made more errors than in the two Mouse conditions. This was particularly true at the beginning of training and for the Keyboard-RLT condition.

Fig. 4 presents the means of median RTs for the four conditions. A 2 (Response Device) \( \times \) 2 (Tone) \( \times \) 10 (Practice Block) ANOVA with median RT as the dependent variable revealed significant main effects of Response Device (\( F(1,79) = 15.92, \) MSe = 154487.5, \( p < .01, \eta_p^2 = 0.17 \)), of Tone (\( F(1,79) = 5.47, \) MSe = 154,487.5, \( p < .05, \eta_p^2 = 0.06 \)), and of Practice (\( F(9,711) = 122.63, \) MSe = 4936.0, \( p < .01, \eta_p^2 = 0.61 \)). No other effect reached level of significance. Thus, participants in the two Mouse conditions responded faster to the stimuli than participants in the two Keyboard conditions. In addition, the picture-tone association enhanced task performance in both Response device conditions suggesting that this association might have facilitated response selection.

To summarize, due to the visual sequence presented in Experiment 2, participants in both PT conditions heard a repeating melody during training because the tones were associated with the pictures of the response squares. Arguably, this should facilitate discovery of the visual sequence in both the Mouse and the Keyboard conditions. However, the results of the wagering task showed that this was the case only in the Mouse condition. In the Keyboard condition, no such benefit was found. These findings further support our assumption that the Keyboard and the Mouse conditions differ with regard to their representation of the S–R binding. Participants in the Keyboard condition represent the pattern of the response squares only as a means of mapping the location of the response square announced by the target to the respective key location. Consequently, the tones did not enhance the relationship between their last response and the subsequently occurring target. By contrast, participants in the Mouse condition represent the pattern of the response squares in their stimulus–response bindings because the pattern announced by the target is the goal for their mouse movement.

5. Experiment 3

The goal of Experiment 3 was to examine the contribution of our response device manipulation (and thus of the S–R binding) on the acquisition of implicit and explicit knowledge. The findings of Haider et al. (2012) suggested that after excluding

### Table 4

Mean percent error rates and standard deviations (in parentheses) as a function of training block and condition in the training phase of Experiment 2.

<table>
<thead>
<tr>
<th>Practice Block</th>
<th>Condition</th>
<th>Mouse-PT</th>
<th>Mouse-RLT</th>
<th>Keyboard-PT</th>
<th>Keyboard-RLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Block 1</td>
<td></td>
<td>2.61 (2.40)</td>
<td>2.50 (2.65)</td>
<td>7.78 (3.29)</td>
<td>12.94 (11.67)</td>
</tr>
<tr>
<td>Block 2</td>
<td></td>
<td>1.61 (1.63)</td>
<td>2.39 (3.70)</td>
<td>6.97 (3.98)</td>
<td>7.32 (6.02)</td>
</tr>
<tr>
<td>Block 3</td>
<td></td>
<td>1.56 (1.50)</td>
<td>1.78 (3.39)</td>
<td>5.90 (4.07)</td>
<td>7.26 (4.88)</td>
</tr>
<tr>
<td>Block 4</td>
<td></td>
<td>2.06 (1.41)</td>
<td>1.83 (3.46)</td>
<td>5.17 (3.08)</td>
<td>5.62 (3.94)</td>
</tr>
<tr>
<td>Block 5</td>
<td></td>
<td>1.22 (1.80)</td>
<td>1.56 (1.89)</td>
<td>4.74 (3.27)</td>
<td>4.31 (2.99)</td>
</tr>
<tr>
<td>Block 6</td>
<td></td>
<td>1.39 (1.90)</td>
<td>1.89 (1.94)</td>
<td>5.00 (3.75)</td>
<td>4.97 (3.58)</td>
</tr>
<tr>
<td>Block 7</td>
<td></td>
<td>1.56 (2.63)</td>
<td>1.28 (1.85)</td>
<td>4.79 (3.25)</td>
<td>4.51 (2.90)</td>
</tr>
<tr>
<td>Block 8</td>
<td></td>
<td>1.11 (1.61)</td>
<td>2.28 (4.02)</td>
<td>5.30 (3.04)</td>
<td>5.16 (3.75)</td>
</tr>
<tr>
<td>Block 9</td>
<td></td>
<td>1.28 (1.70)</td>
<td>2.11 (3.66)</td>
<td>5.39 (3.93)</td>
<td>5.16 (3.51)</td>
</tr>
<tr>
<td>Block 10</td>
<td></td>
<td>1.44 (3.02)</td>
<td>2.17 (2.83)</td>
<td>4.70 (3.04)</td>
<td>5.16 (4.68)</td>
</tr>
</tbody>
</table>

Fig. 4. Means of median RTs as a function of condition and training block in the training phase of Experiment 2. Error bars are the 95% within-participants confidence intervals (Loftus & Masson, 1994).
all participants with explicit knowledge in their experiments, the knowledge advantage for the Mouse condition almost entirely vanished, even though the remaining participants did have implicit knowledge about the visual sequence (see, Zirngibl & Koch, 2002 for similar findings). Therefore, it seems justified to surmise that our response device manipulation promoted the development of explicit knowledge probably without affecting the acquisition of implicit knowledge.

To examine this possibility, participants again received only the visual sequence. We compared two conditions within the two response device conditions: In the first two response device conditions, participants received 50% deviant (or random) and 50% sequence trials (Deviant conditions) that were presented in short alternating runs of 22 trials within each of 8 blocks (leading to overall 704 sequence trials). The second two response device conditions served as control conditions in which participants received only sequence trials (Control conditions). Length of training for Deviant and Control conditions was equalized such that all conditions received the same number of regular sequence trials (700 trials).

If our response device manipulation affects the acquisition of sequence knowledge per se, we should find more sequence knowledge in the two Mouse conditions compared to the two Keyboard conditions. In addition, we should also find more knowledge in the Control conditions than in the Deviant conditions if the deviant trials lead to more noise and thus reduce strength accumulation. By contrast, a finding that only the two Control conditions but not the Deviant conditions differ with regard to the amount of sequence knowledge acquired in the Mouse and Keyboard conditions respectively would be difficult to reconcile with the assumption that our response device manipulation affected the acquisition of knowledge per se. Rather, it would support the findings of Haider et al. (2012) and Zirngibl and Koch (2002) that the response device manipulation mainly influences the acquisition of explicit knowledge without affecting implicit learning processes.

5.1. Method

5.1.1. Participants

Ninety students (17 men) of the University of Cologne participated in the experiment. Mean age of participants was 22.5 (SD = 2.9). None of the participants had participated in previous SRTT experiments, and no one reported being color-blind. As in the earlier experiments, students received either course credit or €5 for participation and could earn some extra money in the wagering task. Participants were randomly assigned either to the Mouse-deviant, to the Mouse-control, to the Keyboard-deviant, or to the Keyboard-control conditions.

5.1.2. Materials and procedure

Material and procedure were identical to the visual conditions of Experiment 1. The only difference was that participants in the two Deviant conditions received short alternating runs of 22 trials that either contained only sequence trials or random trials (Rose et al., 2011). The generation of random trials followed two constraints: (a) No direct repetition of responses or pictures occurred, and (b) the frequency of the six pictures was equalized to that of the regular sequence blocks. Participants received eight blocks overall each composed of 4 repetitions of the sequence and the random runs which were presented in alternating order. After each block, they could take a short break. Thus, training in the two Deviant conditions contained 704 sequence trials (8 blocks with 4 repetitions of the regular sequence runs). We equalized the length of training of the two Control conditions. Participants received seven blocks with 100 trials each, resulting in 700 sequence trials per condition. As in Experiments 1 and 2, half of the participants responded with the mouse, whereas the other half pressed keys on the keyboard. After training, the wagering task was administered.

5.2. Results and discussion

Again, we first analyzed participants’ error rates. Overall, six participants exceeded our error criterion of 15% errors within all blocks. In addition, two participants misunderstood the instructions for the wagering task and two further participants had to be excluded due to disturbances during the experiment. There were 22 participants in the Mouse-deviant, 21 in the Keyboard-deviant, 18 in the Mouse-control, and 19 in the Keyboard-control conditions. For these participants, we individually computed mean error rates and median response times per block. As we did for the first two experiments, we first report the results of the wagering task and then present the results concerning error rates and latencies in the training blocks.

5.2.1. Knowledge in the wagering task

Table 5 shows the results of the wagering task. Again, the first column refers to overall mean percent correct responses, and the second and third column to mean percent correct responses for high and low wagers respectively. A 2 (Response Device: Mouse vs. Keyboard) × 2 (Condition: Deviant vs. Control) ANOVA with percent correct responses as the dependent variable yielded significant main effects of Response Device (F(1,76) = 29.51; MSe = 0.027, p < .01, ηp² = 0.28), and of Condition (F(1,76) = 17.58; MSe = 0.027, p < .01, ηp² = 0.19). In addition, the interaction between Response Device and Condition was also significant (F(1,76) = 17.66; MSe = 0.027, p < .01, ηp² = 0.19). A priori contrasts revealed that the two Deviant conditions did not differ regarding their expressed knowledge (F < 1), whereas the two Control conditions did (F(1,76) = 43.18; MSe = 0.027, p < .01, ηp² = 0.36). Thus, the knowledge advantage for the Mouse condition almost entirely disappeared when participants received 50% deviant trials. By contrast, the Keyboard-deviant and Keyboard-control conditions did not differ regarding the amount of knowledge (F < 1).
The additional 2 (Response Device) × 2 (Condition) × 2 (Wager) ANOVA with percent correct responses as the dependent variable revealed a significant main effect of Wager (F(1,76) = 22.19, MSe = 0.033, p < .01, g_p^2 = 0.23). In addition, the two-way interactions between Response Device and Wager (F(1,76) = 19.81, MSe = 0.033, p < .01, g_p^2 = 0.21), and between Condition and Wager (F(1,76) = 11.24, MSe = 0.033, p < .01, g_p^2 = 0.13) were significant, as was the three-way interaction between Response Device, Condition, and Wager (F(1,76) = 9.01, MSe = 0.033, p < .01, g_p^2 = 0.11). Separately conducted interaction contrasts (Response Device × Wager) revealed no difference between the Mouse-deviant and the Keyboard-deviant conditions (F < 1.5, p = .2861). By contrast, the same interaction contrast was highly significant for the two Control conditions (F(1,76) = 25.90, MSe = 0.033, p < .01, g_p^2 = 0.25). Again, it was only participants of the Mouse-deviant condition who were affected by the interspersed deviant trials.

Thus, the findings of the wagering task revealed that the Mouse-deviant condition did not differ from the Keyboard-deviant conditions even though the two Control conditions did differ from one another. This was mainly due to the large reduction in the amount of knowledge in the Mouse-deviant condition. Participants in the Keyboard-deviant condition did not show such reduction in knowledge. In addition, we found 7 participants with entirely explicit knowledge who were all in the Mouse-control condition.

5.2.2. Error rates and latencies in the training blocks

As the number of blocks during training differed between Deviant and Control conditions (7 vs. 8 practice blocks) and the fact that we were mainly interested in the results of the two Deviant conditions, we report the mean error rates and mean RTs for all four conditions, but restrict the report of our statistical results to the two Deviant conditions.

Table 6 presents the mean error percent per block in the two Deviant (separately for sequence and random trials) and the two Control conditions. Mean error rates ranged between 0.6% and 7.9% (see Table 6).

A 2 (Response Device: Mouse vs. Keyboard) × 2 (Trial Type) × 8 (Practice Block) ANOVA with error rate as the dependent variable yielded significant main effects of Response Device (F(1,41) = 45.23, MSe = .006, p < .01, g_p^2 = 0.52) and of Practice Block (F(7,287) = 9.733, MSe = .0005, p < .01, g_p^2 = 0.19). The Response Device × Practice Block interaction was also significant (F(7,287) = 4.18, MSe = .0005, p < .01, g_p^2 = 0.09). This indicates once again that, participants in the Keyboard condition made more errors than participants in the Mouse condition at the beginning but not at the end of training.

Table 5
Overall mean percent correct responses and standard deviations (in parentheses) as well as percent correct responses when participants placed high or low wagers in the four conditions of Experiment 3.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Percent correct</th>
<th>High wager</th>
<th>Low wager</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mouse deviant</td>
<td>27.78 (7.7)</td>
<td>32.66 (12.5)</td>
<td>24.60 (13.8)</td>
<td>22</td>
</tr>
<tr>
<td>Mouse control</td>
<td>58.49 (30.5)</td>
<td>61.05 (29.1)</td>
<td>16.62 (16.7)</td>
<td>18</td>
</tr>
<tr>
<td>Keyboard deviant</td>
<td>23.28 (7.7)</td>
<td>19.68 (12.1)</td>
<td>19.97 (14.4)</td>
<td>21</td>
</tr>
<tr>
<td>Keyboard control</td>
<td>23.25 (10.4)</td>
<td>22.95 (15.2)</td>
<td>21.24 (11.4)</td>
<td>19</td>
</tr>
</tbody>
</table>

Table 6
Percent error rates and standard deviations (in parentheses) as a function of training block and condition in the training phase of Experiment 3. For means of comparison, errors rates of the two Control conditions are also displayed.

<table>
<thead>
<tr>
<th>Practice Block</th>
<th>Condition</th>
<th>Mouse-deviant</th>
<th>Keyboard-deviant</th>
<th>Mouse-control</th>
<th>Keyboard-control</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Regular</td>
<td>Deviant</td>
<td>Regular</td>
<td>Deviant</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>1.96 (1.93)</td>
<td>2.07 (1.88)</td>
<td>7.90 (5.18)</td>
<td>7.14 (5.06)</td>
<td>3.70 (2.88)</td>
</tr>
<tr>
<td>2</td>
<td>1.45 (1.50)</td>
<td>1.60 (2.34)</td>
<td>5.79 (3.63)</td>
<td>6.49 (3.67)</td>
<td>1.60 (1.71)</td>
</tr>
<tr>
<td>3</td>
<td>1.34 (2.32)</td>
<td>1.14 (1.79)</td>
<td>4.98 (4.14)</td>
<td>6.71 (3.84)</td>
<td>1.05 (1.35)</td>
</tr>
<tr>
<td>4</td>
<td>1.19 (1.66)</td>
<td>1.60 (2.21)</td>
<td>4.55 (4.56)</td>
<td>4.49 (3.12)</td>
<td>1.04 (2.07)</td>
</tr>
<tr>
<td>5</td>
<td>1.19 (2.20)</td>
<td>1.08 (0.96)</td>
<td>3.30 (3.05)</td>
<td>4.60 (2.37)</td>
<td>1.91 (1.65)</td>
</tr>
<tr>
<td>6</td>
<td>1.39 (1.49)</td>
<td>1.55 (1.67)</td>
<td>4.11 (2.29)</td>
<td>4.55 (3.05)</td>
<td>1.11 (1.01)</td>
</tr>
<tr>
<td>7</td>
<td>1.19 (1.33)</td>
<td>0.62 (0.97)</td>
<td>3.84 (2.23)</td>
<td>3.90 (2.75)</td>
<td>1.48 (2.61)</td>
</tr>
<tr>
<td>8</td>
<td>1.08 (1.59)</td>
<td>1.34 (1.34)</td>
<td>5.03 (3.51)</td>
<td>4.55 (2.74)</td>
<td></td>
</tr>
</tbody>
</table>
Fig. 5 depicts the mean RTs for the two Deviant and the two Control conditions. Again, participants in the two Mouse conditions responded faster than participants in the two Keyboard conditions. Furthermore, participants in the two Deviant conditions were slightly faster than participants in the two Control conditions. As we did for error data, we only report the statistical results for the two Deviant conditions.

A 2 (Response Device) × 2 (Trial Type) × 8 (Practice Block) ANOVA with median RT as dependent variable revealed significant main effects of Response Device (F(1,41) = 5.21, MSE = 227,861.9, \( p < .05, \eta_p^2 = 0.11 \)), of Trial Type (F(1,41) = 7.74, MSE = 1434.4, \( p < .01, \eta_p^2 = 0.16 \)), and of Practice Block (F(7,287) = 100.55, MSE = 4041.2, \( p < .01, \eta_p^2 = 0.7 \)). In addition, the interaction between Response Device and Practice Block was significant (F(7,287) = 12.63, MSE = 4041.2, \( p < .01, \eta_p^2 = 0.24 \)), and also the Trial Type × Practice Block interaction was (F(7,287) = 5.47, MSE = 1164.1, \( p < .01, \eta_p^2 = 0.12 \)). Neither the interaction between Response Device and Trial Type nor the three-way interaction was significant (both Fs < 1).

Thus, the Trial Type by Practice Block interaction was not modulated by the Response device factor. This indicates that participants in both Response device conditions showed reliable sequence learning effects that did not differ between conditions. This result additionally solidifies the above reported finding of the wagering task that participants in both Deviant conditions expressed the same amount of knowledge.

To summarize, Experiment 3 provided evidence that the knowledge advantage for the Mouse condition over the Keyboard condition only occurred when participants were trained with pure sequence trials. When participants received the same number of sequence trials that were, however, interspersed with deviant trials, the knowledge advantage for the Mouse condition entirely vanished. Participants in the Mouse-deviant condition showed significantly reduced sequence knowledge compared to the Mouse-control condition and did not differ from the Keyboard-deviant condition. Concurrently, there was no significant difference between the two Keyboard conditions.

Overall, these findings suggest that our response device manipulation affected the generation of explicit knowledge rather than implicit learning. Implicit learning processes seem to be preserved even when participants receive 50% deviant trials, whereas explicit learning was impeded.

6. General discussion

The experiments reported here provided three main results: Experiment 1 showed that participants in the Keyboard and Mouse conditions acquired equivalent amounts of motor sequence knowledge but differed significantly with regard to visual sequence learning. Only in the Keyboard condition was visual sequence knowledge significantly reduced. Experiment 2 further revealed that participants in the Keyboard conditions did not profit from distinctive tones that were contingently associated with the pictures of the visual sequence whereas participants in the Mouse conditions did. Experiment 3 showed that with interspersed deviant trials participants in the two response device conditions learned the visual sequence to the same extent, both in terms of RT-measures and in terms of knowledge expressed in the wagering task. The results further revealed that this alignment of sequence knowledge was due to the Mouse-deviant condition. Participants in this condition no longer had more explicit knowledge even though participants in the Mouse-control condition with equal numbers of sequence trials (just without deviant trials in between) had. In contrast to this reliable reduction of sequence knowledge in the Mouse-deviant condition, the acquisition of sequence knowledge in the Keyboard conditions was entirely unaffected by these deviants.
Overall the entire pattern of results is consistent with our assumption that the task set, and in particular the S–R binding, is critical for the amount of sequence learning in the picture-matching SRTT. Participants acquired more knowledge about the visual sequence when the S–R binding represented the relevant response dimension (i.e., the pictures). In both the Keyboard- and the Mouse conditions, participants must have processed the target picture in order to respond to the correct response square, meaning there was probably no difference in attending to the target picture. However, in the keyboard condition, participants had to press the keys mapped to the response squares and thus might have represented the response key locations in their S–R binding. By contrast, in the mouse condition, the action goal was to move the mouse to a response square which contains a particular color and is located at a certain screen position. Consequently, participants should have represented color and location in their S–R bindings. Overall, our findings nicely fit those of Gaschler et al. (2012), Richard et al. (2009), and Zirngibl and Koch (2002). Additionally, our findings of Experiment 3 suggest that the difference in S–R bindings between the Mouse and the Keyboard conditions altered the development of explicit rather than implicit knowledge.

At least two alternative accounts could be entertained to explain why this difference in S–R bindings influenced the acquisition of explicit sequence knowledge in our visual-matching SRTT: First, it is entirely feasible that the enhanced attention to the pattern of the response square in the Mouse condition strengthened the visual S–S sequence. It might simply be this additional strengthening which, then, would lead to the increased amount of explicit knowledge in the training phase. In Experiment 2, the tones associated with the pictures further strengthened the stimulus–stimulus association as they increased the distinctiveness of the pictures (e.g., Hoffmann et al., 2001; Koch & Hoffmann, 2000; Zirngibl & Koch, 2002). The deviants in Experiment 3 led to more noise which then reduced strength accumulation, resulting in less explicit knowledge in the Mouse-deviant condition. Thus, according to this account, it would be the additional strengthening of S–S learning which increased the amount of explicit sequence knowledge in the Mouse condition. This explanation is quite simple and is consistent with our results.

However, it seems a bit surprising that the additional noise in Experiment 3 did not reduce sequence knowledge in the Keyboard-deviant condition albeit it had such a large effect in the Mouse condition. An explanation based on strength predicts that the deviant trials (or noise) should gradually reduce the amount of acquired sequence knowledge rather than eliminate the development of explicit knowledge. One might therefore argue that our result simply reflects a random effect. However, Haider et al. (2012) and Zirngibl and Koch (2002) also found that, after excluding all participants with entirely explicit knowledge, participants’ knowledge no longer differed between their response device conditions. Thus, it seems not very plausible to assume that the result of Experiment 3 was simply a random finding.

Therefore we propose a second and alternative explanation which is based on response–effect learning (see, Hoffmann et al., 2001; Stöcker & Hoffmann, 2004; Stöcker, Sebald, & Hoffmann, 2003; Ziessler, 1994; Ziessler, 1998; Ziessler and Nattkemper; 2001; Zirngibl & Koch, 2002). Thus far, we have argued that the S–R mappings differ between the Keyboard and the Mouse conditions. What we have not discussed yet is that this difference in S–R mapping leads to one further difference, namely, whether or not participants experience a consistent association between their last response and a subsequent event (R–E associations). If participants in the Keyboard condition encode the location of the response squares as the relevant response dimension, their last response consistently predicts the location of the cued response square in the next trial, given that a motor sequence is built into the task. By contrast, in case of a visual sequence, the location of the last response does not predict anything. The locations of the response squares are arbitrarily mapped to the pictures, and therefore also to the upcoming target. In the Mouse condition in which participants probably represent both the picture and the location of the cued response square, they can experience the R–E contingencies regardless of whether the task contains a motor or a visual sequence. Accordingly, the Mouse and Keyboard response devices do not only differ with regard to the S–R binding but, as a consequence, also with regard to the fact whether or not the last response contingently predicts a subsequent event (i.e., the R–E contingency).

This explanation additionally assumes that S–S (or R–R) and R–E learning might differ regarding important characteristics. Only R–E associations enable participants to predict future events in their environment from their response (Hazeltine, 2002). These predictions are important for the individual as they can lead to voluntary actions and control (e.g., Nattkemper, Ziessler, & Frensch, 2010). Importantly, voluntary actions depend on knowing which action contingently leads to which effect. Therefore, it is conceivable that the contingency between responses and upcoming events affects the exploitation of the R–E contingencies, not the learning of these associations (see, Haider, Frensch, & Joram, 2005). That is, participants only voluntarily rely on R–E associations if the responses reliably predict future events. If not, they will not rely on them. Since S–S (R–R) associations do not contribute to voluntary actions the exploitation of such associations are not impeded by violations of S–S associations. Thus, R–E and S–S (R–R) learning might differ with regard to their vulnerability to deviant trials.

Some evidence relevant to this issue already exists in the literature, supporting our assumption that S–S (R–R) vs. R–E learning might differ. For instance, Abrahamse et al. (2010) note that S–S (R–R) associations are built within the same information processing stages (the encoding of stimuli or the selection of responses) whereas R–E learning refers to associations between the responses and the subsequent stimuli. With reference to Keele, Ivy, Mayr, Hazeltine, and Heuer (2003) dual-system account, Abrahamse et al. (2010) further surmise that S–S (R–R) learning takes place in unidimensional systems which are modality specific and might encode information within one single module. By contrast, R–E learning, as it refers to different information processing stages, requires the multidimensional system which depends on selective attention. That is, Abrahamse et al. (2010) assume that S–S (R–R) learning and R–E learning differ in terms of the underlying system (unidimensional vs. multidimensional system). Further evidence for differences between S–S (R–R) and R–E learning stems from the comparison of classical conditioning (the association between a conditioned and an unconditioned stimulus is compa-
rable to S–S learning and instrumental conditioning (the association between a response and a reward is comparable to R–E learning). For instance, O’Doherty et al. (2004) provided evidence that the underlying neuronal systems might differ between these two forms of learning. Only instrumental conditioning comes along with activations in the dorsal striatum which is assumed to be involved in cognitive control.

Thus, at least some evidence exists that S–S and R–E learning processes might differ. If so, this would nicely explain our findings concerning visual sequence learning. In Experiments 1 and 2, the responses in the Mouse condition consistently predicted the next target which then enabled participants to voluntarily rely on these R–E associations. This change to voluntary action comes along with explicit knowledge about the visual sequence. In Experiment 3, however, the 50% deviant trials might have hindered the voluntary exploitation of the R–E contingencies such that mainly the S–S associations contributed to the learning effects observed in this experiment. As only participants in the Mouse conditions had profited from the additional R–E associations in Experiments 1 and 2, the difference between the Mouse and the Keyboard condition disappeared in Experiment 3.

Therefore, at least in our experiments, it may be the R–E associations which have the capability to mediate between implicit visual sequence knowledge and explicit or conscious knowledge. They mediate between implicit and explicit knowledge, because they lead to the prediction of future events which are observable in the environment (e.g., Downing, 2013). This R–E learning probably does not change the representation of the implicitly acquired knowledge as is, for instance, proposed by Hoffmann et al. (2001) or Zirngibl and Koch (2002). Rather it leads to additional representations which might have the capability to become consciously accessible as they connect responses with events in the environment and are thus inter-dimensional representations (e.g., Abrahamse et al., 2010). However, further research is needed to test these assumptions.

The motor sequence usually used in the SRTT makes it difficult to separately examine the contribution of different learning mechanisms. Response–effect learning is inextricably present in implicit motor learning because regular stimulus–response mappings always imply regular response–effect associations. It is therefore unclear whether, for instance, spatially incompatible response mappings as used by, for instance, Hoffmann and Koch (1997) or Koch (2007) enhanced implicit learning effects by forcing more demanding response selection processes (i.e., enhancing the R–R learning effect), or whether this demanding response selection process led to more distinctive representations of the responses which, in turn, facilitated R–E learning. Here, too, further research is needed to clarify this point.

One additional point concerning our current results should get some attention. In all three experiments, we used abstract and hard-to-name stimuli. We did so because we were interested in the question whether the generation of entirely conscious sequence representations requires the transformation of visual information into verbal codes. Many researchers assume that consciousness is equivalent to verbal report (e.g., Edelman, 2003; Rünger & Frensch, 2010). However, our findings speak against this assumption. In our experiments, participants with entirely explicit knowledge clearly did know that they know the sequence but were completely unable to describe it verbally. Thus, our results seem to suggest that participants had acquired a higher-order representation (e.g., Dienes & Perner, 1999; Lau & Rosenthal, 2011), but that this representation was independent of verbal codes.

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