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Context-dependent motor skill and the role of practice

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Abstract Research has shown that retrieval of learned information is better when the original learning context is reinstated during testing than when this context is changed. Recently, such contextual dependencies have also been found for perceptual-motor behavior. The current study investigated the nature of context-dependent learning in the discrete sequence production task, and in addition examined whether the amount of practice affects the extent to which sequences are sensitive to contextual alterations. It was found that changing contextual cues—but not the removal of such cues—had a detrimental effect on performance. Moreover, this effect was observed only after limited practice, but not after extensive practice. Our findings support the notion of a novel type of context-dependent learning during initial motor skill acquisition and demonstrate that this context-dependence reduces with practice. It is proposed that a gradual development with practice from stimulus-driven to representation-driven sequence execution underlies this practice effect.

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Introduction

It has often been observed that performance of a learned skill is better when the learning context is reinstated at test as opposed to testing in another environment (Smith & Vela, 2001). Such contextual dependencies have been demonstrated for verbal memory performance using contexts like physical environment (Godden & Baddeley, 1975), physiological state (Eich, 1980), and background music (Smith, 1985). In addition, contextual dependencies have been reported for perceptual-motor skills (e.g., Abrahamse & Verwey, 2008; Anderson, Wright, & Immink, 1998; Wright & Shea, 1991). One major aspect of motor skill involves sequence learning, i.e., the acquisition of serially organized behavior. Most complex motor actions that people perform in daily life (e.g., writing, driving, and playing guitar) consist of a series of simple movements that are executed in a specific sequential order. The present study investigated, first, the nature of context-dependent learning in sequencing skill, and second, the role of the amount of practice in the extent to which sequencing skill becomes context-dependent.

A number of studies have explored context-dependent learning in perceptual-motor sequence learning tasks. In the studies of Anderson et al. (1998) and Wright and Shea (1991) the intentional—that is, imperative—feature of each stimulus in the learned sequence was the spatial location on the screen (using four horizontally outlined location markers) and participants responded with a spatially compatible key press. Stimulus displays in these two studies also involved incidental stimulus features—features that are not essential for successful task performance—namely background color, accompanying tone, and shape and position of the stimuli on the screen (top, middle or bottom). Participants practiced three 4-key sequences, each

sequence within a unique combination of incidental features. Sequencing performance decreased when these incidental features were changed in a subsequent test phase, thus indicating context-dependent sequence learning.[1] In another sequencing study, Abrahamse and Verwey (2008) used a serial reaction time (SRT) task to explore context-dependent learning with static stimulus features. In an SRT task, participants perform a location-based choice RT task in which the stimulus order is fixed (e.g., Nissen & Bullemer, 1987). Though participants are often unaware of (the precise nature of) this order, learning is witnessed by performance measures—this type of learning is called implicit learning (e.g., Destrebecqz & Cleeremans, 2001). Abrahamse and Verwey (2008) showed that implicit learning can be context-dependent, as task-irrelevant changes in the stimulus display reduced performance.

The observation that skilled performance benefits from reinstatement of the context in which it was acquired, and that the skill cannot fully be transferred to another context, has been referred to by the concepts of context-dependent learning (e.g., Wright & Shea, 1991), procedural reinstatement (e.g., Healy, Wohldmann, Parker, & Bourne, 2005) and specificity of learning (e.g., Healy et al., 2005). They all adhere to the general principle that transfer occurs to the extent that there is overlap in features between training and testing. The common explanation of context-dependent learning is that context cues become associated with the task due to their mere presence during task acquisition, and subsequently facilitate memory retrieval processes (e.g., Healy et al., 2005; Wright & Shea, 1991). When these cues are changed during testing, this may hinder retrieval of the learned skill from memory, thereby resulting in impaired performance. We refer to this mechanism as *context-dependent retrieval*.

It could be theorized, however, that performance and context-dependent learning processes are related to each other in yet another way that—to the best of our knowledge—has not been recognized so far. This notion is inspired by the SRT studies of Cock, Berry and Buchner (2002) and Deroost, Zeischka and Soetens (2008). In otherwise typical SRT tasks, these researchers presented irrelevant stimuli simultaneously with the imperative stimuli, at another location and in a different color. It was shown that people could learn to ignore the sequence of locations of the irrelevant stimuli, as later responding to this sequence of previously irrelevant locations was impaired relative to fully unfamiliar (or random) sequences. This learning process, which they termed negative priming, predicts that performance should be impaired when the locations of irrelevant stimuli (i.e., the "context") are changed after practice. Hence, this strongly suggests a second relationship between performance and context-dependent learning: context is initially interfering with optimal performance (e.g., because it forces a visual search), but people learn to cope with such interference through biasing attentional selection by means of a filter. This would imply that after changing the context, the filter may no longer work and the performance drops. As a first goal of this study, we aim to explore the prospect of such *context-dependent filtering* as a potential second type of context-dependent learning—besides the more common notion of context-dependent retrieval.

The second goal of this study relates to the role of practice in context-dependent learning of discrete movement sequences. Wright and Shea (1991) hinted at the possibility that the amount of practice modulates context-dependent learning, and specifically that context dependency decreases as practice progresses. This notion is in line with work of Fitts and Posner (1967) who proposed that during initial motor skill learning specific environmental cues become associated with the required movements. With extended practice, however, automaticity is reached: the skill can be performed without attention and—more important for the present study—without dependence on environmental cues. Support for such a shift from controlled to more automated skill execution comes from the finding that with extensive practice, people can execute discrete keying sequences without the aid of key-specific cues (Verwey, 1999, 2010). While initially using each key-specific cue for executing individual sequence elements (i.e., the reaction mode), people shift to executing the entire sequence in response to (just) the first stimulus, while ignoring subsequent stimuli (i.e., the sequencing/chunking mode). Similarly, Hikosaka et al. (1999) proposed that a sequential skill starts off from visual-spatial coordinates and with further practice becomes increasingly motor based and therewith less stimulus-dependent. The need for environmental cues thus decreases, implying that the skill would become less susceptible to contextual changes. Therefore, and in line with Wright and Shea's (1991) prediction, we hypothesize that contextual dependencies in sequencing skill performance gradually reduce with practice.

In the current study, we employed a discrete sequence production (DSP) task to explore (a) the prospect of two distinct types of context-dependent learning, and (b) the role of practice. This task is highly suitable for studying the

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[1] One may doubt, however, whether this effect truly involved the effect of incidental context, as the "incidental" features possibly became intentional over time. That is, participants may have used (one of) these features for sequence identification and/or execution as they probably required less effort to be processed compared to the intentional feature. In line with this possibility, Ruitenberg, Verwey and Abrahamse (unpublished work) found no indications of context-dependent sequence learning when the incidental context was static during training (i.e., all sequences were trained within the same context), and could therefore not be used for sequence identification.

processes underlying motor sequence learning as it allows the development of automated skill in a relatively controlled setting (for a more detailed discussion, see Verwey, Abrahamse, & De Kleine, 2010). In its typical version, participants are presented two sequences of two to seven stimuli in a fixed order to which they respond by means of spatially compatible key presses. With practice, the sequences are learned and execution rates increase. It is assumed that improvement occurs because familiar series of key presses are represented in a single memory representation, called a motor chunk (e.g., Verwey, 1999). In order to induce context dependency in the present study, we presented the irrelevant stimuli on the same spatial dimension as the relevant stimuli. According to the principle of intentional weighting (i.e., top–down selection of task-relevant feature dimensions; Hommel, Müsseler, Aschersleben, & Prinz, 2001) this should ensure that the incidental information is encoded during task execution, as it is assigned the same weight as the intentional information. Hence, while usually only one stimulus is presented per display, we presented two differently colored stimuli simultaneously—one intentional and one incidental stimulus—in an otherwise standard DSP task. The role of practice was explored by manipulating the number of practice blocks between different practice groups, and the test phase involved three distinct conditions to explore context-dependent retrieval and filtering.

First, in the *changed context condition* we presented the irrelevant stimuli at different locations compared to the practice phase. Second, in the *removed context condition* we simply removed all irrelevant stimuli. Finally, the performance on these two test conditions was compared to a third test condition in which nothing changed relative to practice, the *same context condition*. According to the notion of context-dependent retrieval, similar performance impairments should occur for both the changed and removed context conditions in the test phase, as both are characterized by removing the incidental cues that are supposed to facilitate memory retrieval. Conversely, from the notion of context-dependent filtering, predictions are less straightforward as different filtering strategies may be used. First, if a *location-based filter* is adopted—as can be expected from the studies of Cock et al. (2002) and Deroost et al. (2008)—we predict that changing the context adversely affects performance because the novel irrelevant stimulus locations do not match the learned-to-ignore locations, and people thus have to learn anew to cope with this novel situation (i.e., they have to learn to ignore another series of locations). Removing the irrelevant information, however, should not impact performance as it does not require renewed learning and application of the acquired filter should not lead to interference. Second, it could also be speculated that people adopt a *color-based filter*, learning to ignore all stimuli with a specific color or only attending to the target color. In this case, one would expect similar performance irrespective of whether irrelevant stimuli are changed, removed, or left intact in the test phase (relative to practice).

Overall, in the present study we explored, first, whether learning to deal with an interfering context may constitute another type of context-dependent learning than the typical interpretation in terms of memory retrieval. As outlined above, the test phase of the current study nicely predicts different outcomes for context-dependent facilitation, location-based filtering, and color-based filtering. Second, we explore the precise role of practice in context-dependent learning, predicting that contextual dependencies reduce with practice as sequence execution gradually becomes less dependent on external stimulation.

Method

Participants

Participants were 48 students (17 male, 31 female) of the Faculty of Behavioral Sciences at the University of Twente. They were aged 18–27 years ($M = 22$) and participated as part of a course requirement. According to Annett's (1970) Handedness Inventory 44 subjects were right handed, two were left handed and two were ambidextrous.[2] All participants gave their written informed consent and reported not having problems with their sight (corrections via glasses or contact lenses were allowed). The study was approved by the ethics committee of the Faculty of Behavioral Sciences of the University of Twente.

Apparatus

We used E-Prime© 2.0 for stimulus presentation and data registration. The program ran on a Pentium IV class PC. Stimuli were presented on a 17-in Philips 107 T5 display.

Task and procedure

At the start of the experiment, all participants were instructed to place the little, ring, middle and index fingers of their left hand on the c, v, b and n keys, respectively. Four horizontally aligned white square stimulus placeholders were presented against a black background, and each key corresponded to a specific stimulus location on the screen. Two of the stimulus placeholders were then filled with a color, one with red and one with blue. Half of the

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[2] Removing the left-handed and ambidextrous participants from the analyses did not yield a different pattern of results.

participants responded to the red square and the other half to the blue square (i.e., the relevant stimulus). They were not informed about the other colored square (i.e., the irrelevant stimulus). A correct response to each relevant stimulus was given by pressing the corresponding key, e.g., c, for the leftmost square. Immediately after a response was given, the next combination of relevant and irrelevant stimuli in the sequence was presented. Following a correct response to the last stimulus of each sequence, the stimulus placeholders were presented for 1,000 ms before the first combination of relevant and irrelevant stimuli of the next sequence was displayed. The relevant and irrelevant stimuli were consistently matched throughout practice, so that each relevant sequence was paired with only one irrelevant sequence.

Participants were instructed to respond as fast and as accurately as possible. They received feedback regarding mean response time and accuracy before each break. If a participant's error rate was below 3% or above 8%, a message stating "respond faster" or "respond more accurately" was shown, respectively.

In the practice phase, participants learned two 7-key sequences of a fixed order. To prevent finger-specific effects on individual sequence locations, we created four versions of one sequence (*vnbnvbc*, *nvcvncb*, *bcncbnv* and *cbvbcvn*), two of which were presented to each participant as relevant sequences and two as irrelevant sequences. Across participants each sequence was as often relevant as irrelevant. Half of the participants practiced 100 trials of each sequence, distributed across two blocks. The other half practiced 300 trials of each sequence, distributed across six blocks.

The test phase consisted of three test blocks (see Fig. 1). In the *same context* test block, the relevant and irrelevant sequences were identical to those in the practice phase. In the *changed context* test block, the relevant sequences were paired with new irrelevant sequences, consisting of
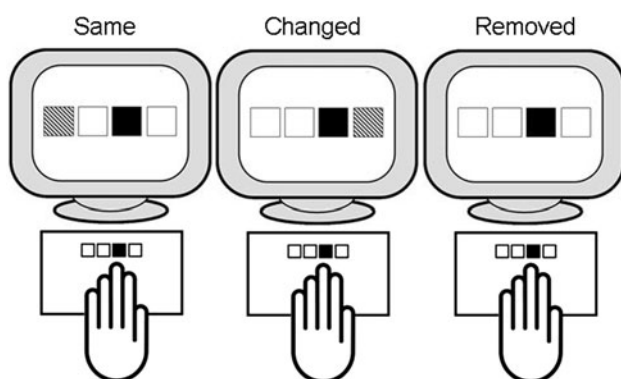
Fig. 1 An example of a single stimulus within a sequence for the same, changed and removed context test conditions. The *black square* is the intentional stimulus, while the *striped square* is the incidental stimulus

mirrored versions of the old irrelevant sequences. Finally, there was a *removed context* test block in which only the learned sequences were shown while the irrelevant stimuli were removed. The order of the test blocks was fully counterbalanced over participants. Finally, participants completed a questionnaire, in which they were asked to recall both the relevant and accompanying irrelevant sequences.

Each block (both practice and test) included 50 trials per sequence, which were presented in a random order. There was a short 30-s break halfway through each block and a 3-min break in between blocks.

Data analysis

The first two trials (i.e., sequences) of every block and the first two trials directly following a pause were discarded from the analyses. Additionally, we eliminated trials in which one or more errors had been made. We calculated mean response times (RTs) per key within the sequences for every participant in each block. RT was defined as the time between stimulus presentation and depression of the appropriate response key. To analyze the practice and test phase, mixed factorial analyses of variance (ANOVAs) were performed. Planned comparisons were performed to specifically address our hypotheses.

Results

Practice phase

For the limited and extended practice condition ANOVAs with Block (2 or 6) and Key (7) were performed. As Fig. 2 shows, mean RTs decreased across the practice blocks, $F(1,23) = 167.42$, $p < .001$ for limited practice and $F(5,110) = 126.38$, $p < .001$ for extended practice. Some key presses were executed faster than others, $F(6,138) = 11.20$, $p < .001$ for limited practice and $F(6,132) = 27.76$, $p < .001$ for extended practice. A Block × Key interaction suggested that across the blocks some keys improved more than others, $F(6,138) = 10.67$, $p < .001$ and $F(30,660) = 12.41$, $p < .001$ for limited and extended practice, respectively (see Fig. 2). Finally, an ANOVA on the first two practice blocks with Block (2), Key (7) and Practice (2; limited vs. extended) showed no main or interaction effects of Practice, $p_s > .13$, suggesting that performance of the practice groups on these blocks did not differ.

Test phase

Results of an ANOVA on RTs with Test condition (3), Key (7) and Practice (2) showed that participants responded faster
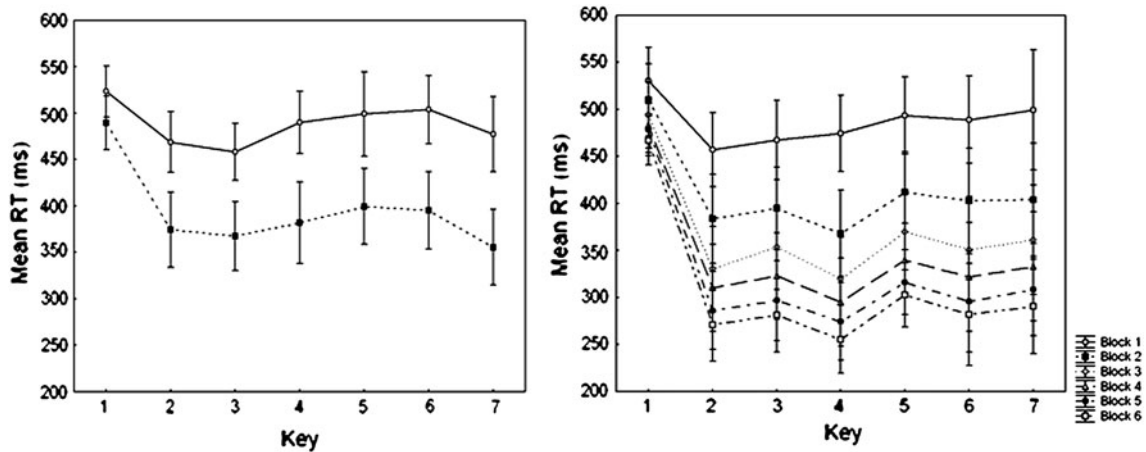
Fig. 2 Mean RT per key as a function of practice block for both the limited (*left panel*) and extended (*right panel*) practice condition. *Error bars* represent standard errors

after extended practice than after limited practice (280 vs. 330 ms), $F(1,46) = 6.41$, $p < .05$. Performance in the various test conditions differed (299 vs. 318 vs. 297 ms for the same, changed and removed context, respectively), $F(2,92) = 8.38$, $p < .001$. Moreover, a Test condition × Practice interaction suggested that the differences in performance on the test conditions were dependent on prior practice, $F(2,92) = 3.44$, $p < .05$ (see Fig. 3). Some key presses were executed faster than others, $F(6,276) = 116.69$, $p < .001$. This effect is likely to be caused by the longer RT on key 1 as compared to other keys. A Key × Practice interaction suggested that some keys were affected

more by practice than others, $F(6,276) = 4.39$, $p < .001$, and a Test condition × Key interaction indicated that key presses within the sequence were differently affected by the various contexts, $F(12,552) = 4.39$, $p < .001$. Figure 3 suggests that these effects are primarily due to key 1.

To further investigate the aforementioned Test condition × Practice interaction and explore our hypothesis, planned comparisons were performed. First, a planned comparison showed that RTs were shorter in the same than in the changed context, $F(1,46) = 10.61$, $p < .01$. This supports our hypothesis that changing the context affects sequence–skill performance. To further explore the

Fig. 3 Mean RT per key for the same, changed and removed context conditions for both the limited practice (*left panel*) and extended practice (*right panel*) condition. *Error bars* represent standard errors
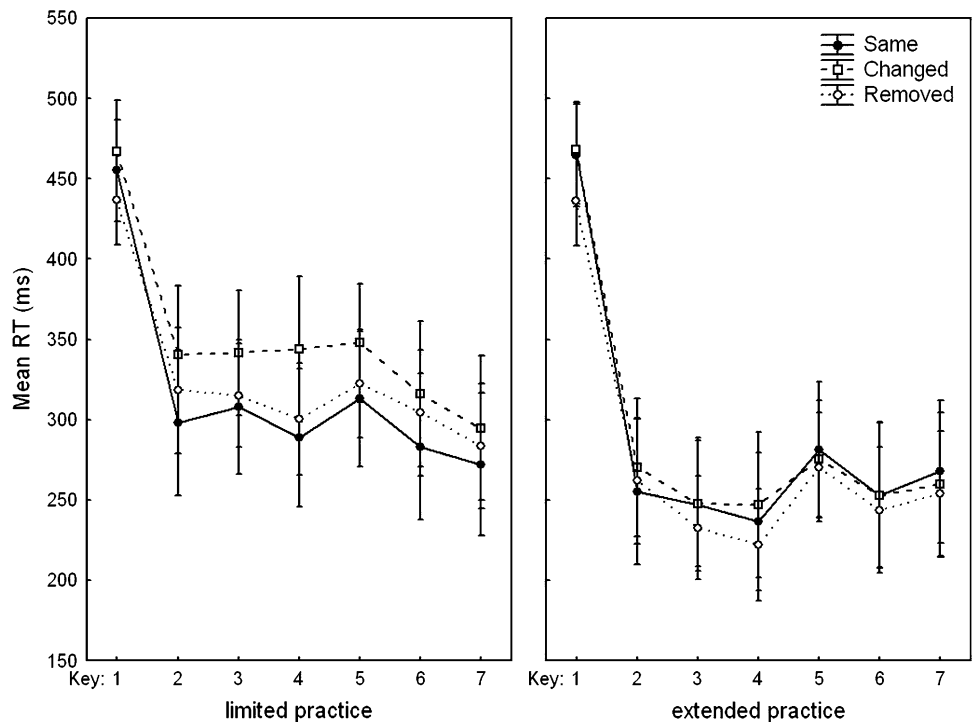
hypothesis that this effect is dependent on the amount of practice, we performed a planned comparison for the limited practice group only. Results showed that performance was significantly better in the same context than in the changed context (316 vs. 350 ms), $F(1,46) = 16.74$, $p < .001$. In contrast, a similar planned comparison for the extended practice group yielded no significant result (282 vs. 286 ms for the same and changed context, respectively), $p = .61$. The interaction between the practice conditions and performance in the same versus changed contexts was significant, $F(1,46) = 6.40$, $p < .05$. Finally, results of a planned comparison showed that performance in the same and removed context did not differ, $p = .71$, neither after limited nor after extended practice, $p_s > .18$. So, while RTs were slower in the changed than in the same and removed context conditions after limited practice, this effect disappeared after more extensive practice.

As the above-mentioned Test condition × Key interaction and inspection of Fig. 3 suggested that key 1 was differently affected by the context manipulations than the other keys, we further examined the difference between key 1 and the other keys. First, we performed an ANOVA on RTs of key 1 with Test condition (3) and Practice (2). Results showed a main effect of Test condition, $F(2,68) = 13.81$, $p < .001$. There were no main or interaction effects of Practice. Paired t tests showed that responses to the first stimulus were faster in the removed context (439 ms) than in the same and changed context (462 and 473 ms), $t_s(47) > 4.79$, $p_s < .001$, while RTs of key 1 in the same and changed context did not differ significantly, $p > .06$. The effect of context on performance thus was different for key 1 compared to the overall context effect, and was uninfluenced by practice. Removing key 1 from the original ANOVA yielded similar results, with significant main effects of Practice, $F(1,46) = 7.17$, $p < .05$, and Test, $F(2,92) = 6.48$, $p < .01$, as well as a significant Practice × Test interaction, $F(2,92) = 3.76$, $p < .05$—hence, verifying that the pattern of practice and context effects was present for keys 2–7. Also, planned comparisons for these keys showed that performance in the same context was better than that in the changed context (272 vs. 292 ms), $F(1,46) = 9.80$, $p < .01$. A similar planned comparison showed a significant difference for the limited practice group (229 vs. 329 ms), $F(1,46) = 16.72$, $p < .001$, but not for the extended practice group, $p > .73$. This interaction was significant as well, $F(1,46) = 7.04$, $p < .05$. Again, there were no differences in performance between the same and removed context, $p = .85$, neither after limited nor after extended practice, $p_s > .23$. So, the effect of practice on context dependency occurs after responding to the first stimulus of a sequence.

Finally, we examined the effects of practice and context on the accuracy of participants' performance in the test conditions, by calculating the proportion of erroneous responses per key in each context condition. The average proportion of errors was 3.1%. Error proportions were submitted to an ANOVA with Test condition (3), Key (7) and Practice (2). Results showed that most errors were made on the second key (4.4% on key 2 vs. 3.5% or less on other keys), $F(6,276) = 5.79$, $p < .001$. There were no other main or interaction effects, $p_s > .21$. Responses to the irrelevant instead of relevant stimulus accounted for 28% of errors in the same and changed contexts. For each context condition, the proportion of responses to irrelevant stimuli was compared to chance level of generating an erroneous response (which is 33% as three keys could be erroneously pressed) with a one-sample t test. Results indicated that in the same context condition the proportion of responses to irrelevant stimuli (26%) were reliably lower than chance level, $t(47) = 2.66$, $p < .001$. In the changed context, however, the responses to the irrelevant stimuli (30%) did not differ from chance level, $p = .14$. This finding suggests that participants have learned not to respond to the locations of to-be-ignored stimuli in the practice phase.

Awareness

Results of the awareness questionnaire showed that in the extended practice group 12 participants (50%) correctly reproduced both relevant sequences and 5 participants (21%) recalled one relevant sequence. Only two participants (8%) in this group correctly recalled both irrelevant sequences and one participant (4%) recalled just one irrelevant sequence. In the limited practice group, nine participants (37%) recalled both relevant sequences and five participants (21%) recalled one relevant sequence. One participant (4%) correctly recalled both irrelevant sequences and one other participant recalled just one irrelevant sequence. For both practice groups, recalling of the relevant sequences was better than recalling of the irrelevant sequences, $t_s(23) > 4.45$, $p_s < .001$. Participants who recalled one or both irrelevant sequences also recalled the accompanying relevant sequences. Differences in performance between the same and changed contexts were not correlated to recall of the relevant, $r(48) = -0.02$, $p = .89$, or irrelevant sequences, $r(35) = -0.08$, $p = .61$, suggesting that performance impairment does not depend on a person's explicit knowledge about the original context.

Discussion

The present study explored context-dependent learning in the DSP task, and provided two major conclusions. First, our data suggest that context effects are not always due to

the facilitation of memory retrieval processes during contextual reinstatement, but also to learning to deal effectively with irrelevant information by means of what we here refer to as a filter. Second, in line with the notion that stimulus information is decreasingly required for proper performance on an automatized skill, we observed that context dependencies diminished as practice increased. These findings provide further empirical support for context-dependent learning of discrete motor sequences (cf. Anderson et al., 1998; Wright & Shea, 1991), and in addition show for the first time that the context dependency of perceptual-motor skill is—at least under some circumstances—modulated by the amount of practice. Below we will discuss these findings in more detail.

We observed that participants' performance in the limited practice group was impaired when irrelevant stimulus locations were changed, but not when they were removed. This provides support for the notion that people can learn to deal effectively with stimulus conflict through context-dependent filtering, by learning to ignore the conflicting information (cf. Cock et al., 2002; Deroost et al., 2008). When the irrelevant information was changed in the test phase, incidental stimulation was no longer received from the expected—and learned-to-ignore—locations, and therefore rendered useless the filter that had developed during practice. Conversely, the performance was unaffected by removal of the irrelevant stimuli (with exception of the first key press), as it did not require renewed learning of to-be-ignored locations and application of the acquired filter did not lead to interference.

An issue for future research may be to understand the mechanism underlying such filtering. One question may relate to what exactly is filtered out? Based on our current results, we believe we can already elaborate on this to some extent. First, it cannot be a color-filter, as the changed context—presented in the same color—negatively affected performance compared to the same context. Second, a filter based on the locations of irrelevant stimuli from the display information can account for the current results: while changing the context required a new conflict to be solved (i.e., new locations had to be ignored), removing the context did not require renewed learning and the strategy of ignoring certain locations thus could still be used without affecting performance. Moreover, the finding that the proportion erroneous responses to irrelevant stimuli was significantly lower than chance level in the learned context, confirms that participants learned not to respond to the to-be-ignored locations during practice. Finally, we cannot exclude the possibility that the filter was based on a combination of color and location features—hence, a sort of task-filter. As noted, future research should aim to further examine the precise nature of this filter.

Another question pertaining to the here proposed filter relates to its precise relationship to the task-relevant information. One possibility is that participants learned to ignore the order of to-be-ignored locations along with the order of relevant stimuli, and thus learned a to-be-ignored sequence (i.e., a spatial–temporal filter; cf. Cock et al., 2002; Deroost et al., 2008). For example, participants could learn that with the first key press of a sequence, the third stimulus location and/or corresponding key press should be inhibited; with the second key press, the fourth location and/or key press should be inhibited; etc. However, in the changed context condition not only the locations of the irrelevant stimuli, but also the coordination of relevant and irrelevant stimuli was different from what participant had learned in the practice phase. That is, while in the practice phase each relevant stimulus location was always paired with one specific irrelevant stimulus location (e.g., relevant 'c' was always paired with irrelevant 'b' in the sequence), this coordination changed during testing (e.g., the first relevant 'c' in the sequence was paired with irrelevant 'b', while the second 'c' was paired with 'v'). Another possibility, then, is that the locations of the irrelevant stimuli were learned relative to those of the relevant stimuli—indicating that the to-be-ignored information could be anticipated through predicting the next task-relevant stimulus (i.e., a purely spatial filter).

Noteworthy is that the current findings do not correspond with the common view on context-dependent learning, namely that retrieval of a skill representation from memory is always facilitated when the original learning context is reinstated (e.g., Healy et al., 2005; Wright & Shea, 1991; see also Abrahamse & Verwey, 2008). It is often claimed that contextual cues are integrated within an overall skill representation, and that the reinstatement of such cues aids retrieval. If in the present study the irrelevant stimuli had indeed been integrated within the sequence representation, one would predict superior performance in the same context condition compared to both the changed and removed context condition, which was not observed. As such, we believe that the results of the current study provide support for a novel type of context-dependent learning, namely context-dependent filtering. Future research should zoom in on both these types of context-dependent learning and investigate under which conditions either type is developed and/or is expressed.

The second goal of the present study was to investigate the role of practice in context-dependent learning. We hypothesized that contextual dependencies would diminish as practice increased (cf. Wright & Shea, 1991) because reliance on external stimuli reduces with practice (Hikosaka et al., 1999; Verwey, 1999). Indeed, contextual dependencies were found only after limited practice and

not after extended practice. As already briefly hinted at in the introduction, we propose that the mechanism underlying the effect of practice on context dependencies (at least within the realm of the DSP task) pertains to the source of evidence that people use for response selection on a trial-by-trial base. Before generating a response, people accumulate evidence (e.g., stimulus color, location) until the required response can be correctly identified (Brown & Heathcote, 2008). Such evidence can be provided both by external information (i.e., a stimulus) and/or by internal information (i.e., a sequence representation). The relative importance of internal evidence increases with practice, as sequence representations gradually become stronger during skill acquisition (see Cleeremans & Jiménez, 2002). Sequence execution thus shifts from being externally driven toward being internally driven (Tubau, Hommel, & López-Moliner, 2007): participants gradually shift from identifying each key-specific stimulus in the reaction mode, to using an internal representation in the sequencing/chunking mode (Hikosaka et al., 1999; Verwey, 1999, 2010). In the latter case, the evidence provided by the sequence representation—the internal information—is sufficient for signaling the appropriate response (cf. Tubau et al., 2007). Participants no longer needed to process stimulus information for the execution of subsequent key presses after initiation of the first key press of the sequence. Consequently, external stimulus information could be mostly ignored and performance was unaffected by either context manipulation.

The increasing independence of stimulus information with practice does not apply to the first key press of a sequence. Participants always performed two sequences, so the first stimulus needed to be processed in order to select the appropriate sequence. Accordingly, we observed that RTs of the first key press of a sequence were actually faster in the removed than in the same and changed context of the current study, irrespective of the amount of prior practice. This suggests that detecting the first imperative stimulus of the sequence involved a visual search procedure when irrelevant stimuli were present. Yet, key presses following the first of a sequence were not significantly affected by removing the irrelevant stimuli, indicating that visual search was not needed for later stimuli. The differential involvement of sequence learning between the first key press and later ones can explain this discrepancy regarding context dependence. The first key press relies on the randomly selected sequences and thus is unpredictable, whereas later key presses can be predicted on the basis of the acquired sequence information—hence, on some internal representation (e.g., a motor chunk). RTs of the first key press were similar in the same and changed context, which is reasonable as detecting the first stimulus involved visual search in both conditions.

It should be noted that the demonstrated effect of practice on context dependence does not necessarily exclude the possibility that the link between learned sequences and their contexts strengthens with practice. It could well be that—even though the link between task and context becomes stronger—changes in context have no or a little effect once a level of automaticity in sequencing skill has been reached. As participants start to build internal sequence representations, the need for using the environment (i.e., the key-specific stimuli on the screen) decreases, thereby resulting in reduced context dependence. This reasoning could apply not only to context-dependent filtering, but also to context-dependent retrieval—though future studies should explore the specific effects of practice on the latter. Moreover, it is important to note that the effects of practice may be task-specific. For tasks in which the stimulus input remains essential even after extensive practice, for example in the case of probabilistic SRT tasks (e.g., Schvaneveldt & Gomez,1998), one would predict to find increasingly stronger effects of context change with practice.

Finally, let us briefly discuss—and counter—two alternative explanations for the current findings. First, one might argue that performance-differences between the test conditions are due merely to continuous distraction by the irrelevant stimuli. However, from such an account one would predict performance in the removed context to be better than in either the same or changed context—yet this was not observed. This led us to interpret findings with the additional notion of a filter that developed with practice to effectively deal with the conflicting information. In addition, a purely attention-based account cannot explain why context dependency would reduce with practice. Second, results of the awareness questionnaire showed that recall of the relevant sequences was better than recall of the irrelevant sequences, but that recall was not correlated with the extent to which the performance was affected by changing the context. This precludes an explanation in terms of awareness and shows that performance impairment upon contextual changes does not depend on whether the original context has actually been explicitly learned.

In summary, the present study demonstrated that sequence learning in the DSP task is initially context-dependent. Results showed that when an irrelevant sequence was presented along with and on the same spatial dimension as an imperative sequence, changing this irrelevant sequence resulted in impaired performance. This indicates that the participants not only learned to perform the relevant sequences, but concurrently learned to ignore the locations of the irrelevant stimuli—thus, supporting the notion of context-dependent filtering. Moreover, the present study showed for the first time that sequence learning becomes less context-dependent with practice. This effect

seems due to a gradual development with practice from stimulus-driven (i.e., based on external information) to representation-driven (i.e., based on internal information) sequence execution (cf. Verwey, 1999; Verwey et al., 2010). Altogether, we thus believe the current results reflect a combination of the notions of (a) a location-based filter and (b) a decreasing importance of external stimuli with practice.

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