On the specificity of perceptual-motor sequence learning

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Abstract

Motor skill expertise developed through practice is supported by implicit learning that leads to gradually improving performance. Previous studies examining this type of learning in the lab have used perceptual-motor sequence learning tasks, such as the Serial Interception Sequence Learning (SISL) task. In the SISL task participants respond to scrolling visual cues that follow a covertly-embedded repeating sequence, and gradually develop improved performance of a specific motor sequence through training. Previous work has demonstrated that altering any component of the motor sequence (e.g. timing) completely disrupts performance, suggesting that this knowledge is extremely inflexible. To test the hypothesis that this specificity extends to the perceptual stimulus component of the sequence, in the current experiment the perceptual information available to participants was selectively manipulated in a test condition that differed from training, while the motor response sequence was left intact. Participants were randomly assigned to train in either the Standard cue condition, with three to four cues on the screen at any time, or the Isolated cue condition, where increased cue velocity only allowed one cue on the screen at any given time. Compared to the sequence expression exhibited during the test that matched their training condition, participants in both conditions exhibited weak transfer to the untrained perceptual condition (~25-30%). This suggests that implicit skill learning leads to integration of information within and across modalities, suggesting that implicit learning will generally be specific to the training context and full transfer of knowledge to different contexts will be difficult to achieve.

keywords: perceptual-motor learning, implicit, transfer, specificity
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Athletes train extensively to perfect the motor skills necessary to succeed at their chosen sport. When practicing, an athlete focuses on a particular skill in order to achieve the desired improvement. The directed practice that leads to motor skill expertise relies on two memory systems. The explicit memory system is responsible for instruction and top-down control; this is the system that typically comes to mind when one thinks of memory because it is how we store facts and events. Explicit knowledge is generally conscious and verbalizable, and is able to be used in a number of contexts (i.e. is flexible). The other memory system is implicit and supports performance improvements through repeated practice (Milner, Squire, & Kandel, 1998; Squire & Knowlton, 2000). This implicit system is generally nonconscious, and produces knowledge that is hard to verbalize. The lack of access to implicit knowledge also tends to be less flexible because there is no conscious access to the representation (Dienes & Berry, 1997).

During skill learning, one uses explicit instructions to learn the rules or guidelines of a motor-skill, such as understanding the basics to hit a serve in tennis (throwing the ball in the air, timing your swing at the ball with the correct coordination, etcetera). Through continued practice, one gains implicit knowledge which leads to improved motor skill performance that eventually becomes automated. Those skills that once were not polished continually improve, and it is difficult to explain what exactly within this continued practice is causing the improvement. These improvements that underlie motor skill expertise are believed to rely on this inflexible, implicit learning. However, it is unclear if this practice will effectively help any other similar skills. For example, even though both a forehand and backhand tennis swing use similar techniques, it is difficult to know how much training your backhand will help your forehand. An
athlete would hope to receive overall benefits from that practiced skill by being able to transfer that knowledge to similar contexts that contain some of the same components.

Perceptual-motor sequence learning has served as an effective task for studying knowledge transfer in skill learning due to its relative simplicity while also allowing for separately manipulable perceptual and response elements. Participants’ learned sequence performance improvements that underlie motor skill expertise are believed to rely on implicit learning. Skill learning is theorized to be developed implicitly through several individual components being learned, such as motor-responses, timing, and perception. By manipulating task demands of perceptual-motor learning tasks, it has been possible to demonstrate learning of individual sequence components and reinforce the separability of component processes.

Research has examined which components can be learned during practiced perceptual-motor sequence knowledge, but the transferability and expression of that knowledge is still in question. Models of transfer are based on the idea that transfer depends on the degree to which the component processes overlap between practice and performance. This is not a novel concept, and in fact is an idea that dates back over 100 years (Woodworth & Thorndike, 1901). Evidence concerning the underlying component processes in complex skill learning tasks can be found by examining transfer effects or failures to transfer from training to test conditions. Limitations in transfer following skill learning likely reflect the inflexibility of implicit knowledge that is best understood using a framework based on examining the overlapping knowledge components between the training context and a performance test.

Sanchez, Gobel, & Reber (2010) demonstrated that the Serial Interception Sequence Learning (SISL) task is a reliable test of implicit perceptual-motor sequence learning. The SISL task is a videogame-like task where participants make timed keypress responses to vertically-
scrolling cues on a computer screen. Unknown to the participants, the cues contain an embedded, intermittent, but repeating sequence to which their performance becomes improved compared to a random sequence of cues. Participants learned their repeated sequence over the course of the experiment and could not reliably indicate which sequence they had trained on. There was no explicit sequence knowledge developed, and participants were only able to express their sequence via performance. Gobel, Sanchez, & Reber (2011) previously found that changing either the order or timing of a learned motor performance in the SISL task eliminates previous practice effects. This result implied a fully integrated representation of action order and timing information that had not been observed in similarly structured studies using a slightly different paradigm (Shin & Ivry, 2002). If transfer is not always predicted simply by the overlapping components, it may also be necessary to account for the possibility of integration of information. If there is learning integration across components, transfer may require consistent information across multiple components. By changing one component of the sequence knowledge, both the transfer of that type of information along with any integrated representations on which it depends are significantly disrupted. This suggests that transfer will often be limited, and indicates that training gains may be restricted to contexts that contain very similar characteristics to training.

Other previous perceptual-motor learning tasks have claimed that learned motor sequence knowledge is entirely represented in response locations (Willingham, Nissen, & Bullemer, 1989; Willingham et al., 2000), which would predict that transfer of knowledge across different conditions would be dependent on maintaining this single component. A perceptual-motor sequence study altered the stimulus presentation from a centrally-located digit during training to four spatially-mapped locations during a transfer test and found reliable sequence knowledge expression in the transfer condition (Willingham, 1999). While this result supports the learning
of response location as a key component of sequence knowledge, the actual amount of transfer was not examined, which opens the possibility that knowledge expression was weaker after the perceptual change.

Additional research has shown the importance of the perceptual-motor component in skill learning, while also examining the specificity of this knowledge. Robust learning of perceptual visual information has been reported (Fiser & Aslin, 2002) and sequence learning studies have found perceptual information to be a learnable sequence component (Deroost & Soetens, 2006). Beilock and Carr (2001) demonstrated that individual knowledge representations can be integral in the performance of learned skill knowledge. Slight changes to perceptual representations (in this case, the shape of a golf putter), while maintaining the exact same weight and motor-response necessary significantly impaired performance.

However, there are some additional benefits to using the SISL task as a measure of implicit skill learning compared to other perceptual-motor learning tasks. Multiple cues are visible on the screen at once which displays perceptual information across multiple sequence items that are specific to the trained sequence. This adds additional contextual information across sequence items and allows for motor planning of upcoming responses, making this information more useful for response completion and thereby potentially making it more likely to become a learned component when compared to other perceptual-motor learning tasks. This suggests that implicit learning processes operating on this more global perceptual information may be acquiring contextual effects of the overall stimuli presentation (Jiménez, Vaquero, & Lupiáñez, 2006), contributing to the set of component processes that must overlap at test in order for trained performance to transfer.
Although it is possible that separate component processes are learning these independent representations, more recent theories propose that an integration mechanism, like the one we propose operates on timing and order in the SISL task, is likely to be binding information across both the stimulus and response information. Integration may be due to learning both separable components and across them (Keele, Ivry, Mayr, Hazeltine, & Heuer, 2003). However, while this predicts learning across separable components, there are no predictions concerning the cost in performance or knowledge execution that may come from a transformation to any of the component processes.

Given the previous studies that found little to no transfer of knowledge in order and timing components, this study would like to examine the learning and following transfer of perceptual component knowledge. The current goal is to test the hypothesis that changing the perceptual characteristics of the task will lead to lower performance in the transfer conditions due to implicit skill learning being specific to training contexts. This experiment will utilize a novel version of the SISL task where only a single cue is visible at a time, compared to the Standard SISL task, where multiple cues are visible on the screen at any time. This experiment selectively manipulates the perceptual information across conditions while maintaining the exact motor response sequence in both (without any change in the order or timing of sequential motor responses). Because this motor response sequence is completely maintained, we would expect to see robust transfer across training and test conditions. However, if there is also integration across perceptual and motor learning components, we would expect the level of transfer to be reduced reflecting learning at the integration level as well as within the individual component processes.
Method

Participants

Thirty participants from the Northwestern University community received $15 for 90-minutes of participation. Two participants were excluded; one due to technical issues during participation and the other did not finish due to leaving early. The data reported are from twenty-eight total participants (19 female, $M_{age} = 20.5$, 26 right-handed).

Materials

The Serial Interception Sequence Learning (SISL) task. This experiment was written in MATLAB© (The Mathworks Inc., 2009) using the Psychophysics Toolbox extensions (Brainard, D. H., 1997). Participants observed circular cues scrolling vertically down a monitor in one of four horizontal locations towards corresponding yellow target rings located near the bottom of the screen. Participants were instructed to use the keyboard and respond with timed keypresses as the cues overlapped the target rings. The responses to cues were performed in correspondence to the keyboard buttons labeled (D,F,J,K). Positive and negative feedback were provided by turning the corresponding ring green if the response was correct or red if the response was incorrect. Response feedback and cue velocity adjustments were based on the correctness of both order and timing. A response provided positive feedback and counted towards an increase in cue velocity if the correct button was pressed within half a short inter-stimulus interval length (initial short ISI, 400 ms) either before or after the cue was optimally-lined up with the target location. If the wrong button was pressed or the correct button was pressed outside of this timing window, then negative feedback was provided and it counted towards a decrease in cue velocity. Performance was assessed every 12 trials throughout training.
and test, and percent correct over 75% led to an increase in speed of 5.0% and performance of 50% correct or worse decreased the speed by 5.0%.

Two variations of the SISL task were used to alter perceptual characteristics of the task while retaining spatial compatibility information and all sequence order and timing response information. The conditions varied by the amount of perceptual information, or the number of cues, on a screen at a time. In both conditions, the cues scrolled down the screen in one of four horizontally-spaced columns, as previously described. In the Standard perceptual condition, there are multiple cues visible on the screen at a time (roughly 3). The Isolated perceptual condition varies in that it only has a single cue visible scrolling down the screen at a time. In other words, the following cue did not appear on the screen until the previous one had disappeared. The timing between responses was kept exactly the same as the Standard version by increasing the overall cue velocity. Thus, the physical distance between cues differs between the conditions in order to alter how many cues are visible at any given time, but the velocity the cues travel at varies between conditions in order to keep the timing between sequence items consistent (see Figure 1). The distance between the tops of two cues separated by a short inter-stimulus interval (ISI) is 130 pixels (two cue lengths), and the initial time it takes the cues to travel across the screen is 1180 ms. However, in the Isolated version the distance between the tops of cues is 465 pixels (7.2 cue lengths) and the initial time it takes the cues to travel across the screen is 330 ms. In both cases, the short ISI is 400 ms.

**Procedure**

The current experiment was conducted in one session that lasted no longer than 90 minutes. Participants first completed short demonstrations of both variations of the SISL task, which each included twenty-four random cues. Participants were then randomly assigned to one
of two training conditions, the Standard, multiple-visible cue condition or the Isolated, single-visible cue condition. In addition, each participant was assigned a 12-item SOC training sequence. The SISL training portion consisted of six 480-trial blocks total. Within each training block there was 384 trials of the training sequence, and 96 trials of novel, non-repeating sequences. Directly after training, participants completed SISL tests of both the Standard and Isolated cue conditions, which were counterbalanced across participants to control for order effects. The SISL tests followed directly after training, and no indication that a test was being administered was provided to the participants. Participants completed four 540-trial test blocks; two blocks on each condition. The first block of each test contained 180-trials of novel, non-repeating sequence trials to allow for cue velocity adjustments between conditions. The remaining 900 trials of each test contained 25 repetitions each of the trained sequence, and two foil sequences, in 60-trial sub-blocks (five sequence repetitions). Participants received 60-second self-terminated rest breaks between all training and test blocks to reduce fatigue.

After completing the SISL training and test portions, participants were informed that a repeating sequence was present in the task they had just completed. All participants then were instructed to complete both a recognition test and a cue-order recall test to assess conscious, explicit, knowledge of the trained sequence. The recognition test consisted of participants observing and performing two sequence repetitions of the SISL task with their trained sequence and also four completely novel order and timing sequences, all of which were presented randomly. Additionally, the test was presented in the participants’ trained SISL condition (Standard or Isolated). After each sequence participants rated how likely the sequence they had just performed was or was not the repeating sequence from their training. Participants rated their
confidence on a scale from -10 (absolutely not the trained sequence) to 10 (absolutely was the trained sequence).

After the recognition test, participants completed an explicit recall task. Participants were shown the same screen as before, with the yellow target rings, however there were no circle cues scrolling down the screen. They were instructed to attempt to generate the trained sequence using the same keypress responses from the SISL task. The recall test ended after the participant entered 24 responses and was scored according to the longest matching subsequence between the participant’s order response and the actual trained sequence order. In order to control for variable abilities in participant recall, we assessed baseline recall knowledge. The participants’ generated sequence was compared to the remaining 201 novel second-order conditional sequences (of 256, as 55 had already been used for novel training sequences and tests) and the average matching subsequence was contrasted for these foils with the target sequence match. Additionally, the recognition and recall tests were counterbalanced for order effects.

Results

SISL Performance

Sequence-specific performance improvements were calculated as the percentage correct difference between the trained sequence and the novel, non-repeating segments across training. A mixed 2x6 ANOVA of condition (Standard, Isolated) and training block (1 through 6) revealed that the sequence-specific benefit increased in a linear trend across training, $F(1,26) = 21.94, p < .001, \eta_p^2 = .46$, and that there was also a main effect of training condition, $F(1, 26) = 7.64, p < .05, \eta_p^2 = .23$, and a significant interaction effect, $F(5, 130) = 2.32, p < .05, \eta_p^2 = .08$, suggesting that learning rates differed between training groups (see Figure 2). To further
examine the high sequence-specific performance advantage in the Isolated condition ($M = 32.89\%, SE = 6.05\%$) compared to the Standard condition ($M = 18.09\%, SE = 3.54\%$) at the end of training, the performance on the training sequence and novel non-repeating sequences was assessed. The trained sequence performance at the end of training in the Isolated condition ($M = 69.83\%, SE = .74\%$) was similar to the trained sequence performance in the Standard condition ($M = 68.51\%, SE = .93\%$), $t(26) = 1.09, p = .29$. However, the novel non-repeating sequences were performed much worse in the Isolated condition ($M = 36.94\%, SE = 5.45\%$) compared to the Standard condition ($M = 50.42\%, SE = 2.97\%$), $t(26) = 2.25, p < .05$.

Sequence performance at test was assessed with a 2x2x2 mixed ANOVA of training condition (Standard, Isolated), sequence type (trained, novel), and test type (same perceptual condition, transfer perceptual condition). Main effects were found for sequence type, $F(1,26) = 58.14, p = < .001, \eta^2_p = .69$, and test type, $F(1,26) = 10.12, p = < .01, \eta^2_p = .28$, but not training condition, $F < 1$. The main effect of sequence type reflects the sequence-specific performance advantage for the trained sequence compared to the foils, and the main effect of test type was due to SISL performance being higher for the trained test condition than the transfer condition. A significant interaction between sequence type and test type, $F(1,26) = 35.66, p = < .001, \eta^2_p = .58$, but no other significant interactions, reflected that the sequence-specific benefit at test was similar across training conditions, and better during the trained condition compared to the transfer condition, as can be seen in Figure 2.

During the test condition where the stimulus display was the same as during training, there were similar sequence-specific performance benefits exhibited by participants in both the Standard training condition ($M = 16.28\%, SE = 2.03\%$) and the Isolated training condition ($M = 20.82\%, SE = 4.30\%$), $ts > 4.85, ps < .001$. As reflected in the interaction effect, this benefit was
reduced during the transfer test in both the Standard ($M = 4.74\%, \ SE = 1.28\%$) and Isolated conditions ($M = 5.49\%, \ SE = 2.82\%$). The sequence-specific performance transfer was significant for participants in the Standard condition, $t(14) = 3.43, \ p < .01$, and while the sequence-specific performance benefit was higher in the transfer condition for the Isolated training participants, the difference only trended towards significance, $t(12) = 1.95, \ p = .08$.

Non-sequence specific learning was assessed as the cue velocity set by the adaptive velocity adjustments. Cue velocity has previously been measured as the time-to-target, but because this variable was manipulated across conditions in order to maintain sequential inter-stimulus-interval timing, the velocity measure reported here is the short inter-stimulus interval. A 2x6 mixed ANOVA (training condition, training block) revealed that the short ISI decreased in a linear trend across training in both conditions, $F(1,26) = 20.49, \ p < .001, \ \eta^2_p = .44$. There was also a main effect of training condition, $F(1,26) = 47.75, \ p < .001, \ \eta^2_p = .65$, but the interaction did not reach significance, $F < 1$, suggesting that while both groups had increases in general task performance, the overall velocity at which the participants performed the task differed across groups. From the initial short ISI of 400 ms, by the end of training participants in the Isolated condition were performing the task with a short ISI of 345 ms ($SE = 16$) while participants in the Standard condition had a mean short ISI of 226 ms ($SE = 5.8$). This difference in velocity was reflected during test across all participants as well, as the Standard version of the SISL task was performed with a much faster short ISI ($M = 254 \ ms, \ SE = 15$), compared to the Isolated version of the SISL task ($M = 402 \ ms, \ SE = 7.7$).

**Explicit Knowledge**

A mixed 2x2 ANOVA of sequence type (trained, foils) and training condition (Standard, Isolated) on the recognition test revealed a main effect of sequence type, $F(1,26) = 38.64, \ p < .
001, $\eta^2 = .60$, suggesting that participants were capable of recognizing their trained sequence. However, a significant interaction effect, $F(1,26) = 5.98, p < .05, \eta^2 = .19$, reflects that the difference in confidence ratings provided by the Standard group to the trained sequence ($M = 4.13, SE = 1.19$) and foil sequences ($M = -.15, SE = 1.11$) was not as large as the difference in confidence ratings by the Isolated group (trained, $M = 6.46, SE = 1.25$; foils, $M = -3.35, SE = 1.29$), suggesting that participants in the Isolated training condition were significantly better at recognizing their trained sequence. The main effect of training condition was not significant. A 2x2 ANOVA of the recall data showed significant main effects for both sequence type (trained, foils), $F(1,26) = 8.54, p < .01, \eta^2 = .25$, and training condition (Standard, Isolated), $F(1,26) = 5.68, p < .05, \eta^2 = .18$ and a significant interaction effect, $F(1,26) = 4.59, p < .05, \eta^2 = .15$. The ANOVA reflects the longest matching subsequence recalled by participants in the Isolated condition matched the trained sequence ($M = 6.92$ items, $SE = 1.00$) significantly better than foil sequences ($M = 4.41$ items, $SE = .06$), $t(12) = 2.49, p < .05$, while the participants in the Standard condition recalled a subsequence that matched both the trained sequence ($M = 4.67$ items, $SE = .32$) and foil sequences ($M = 4.28$ items, $SE = .08$) at roughly similar levels, $t(15) = 1.29, p = .22$.

In order to assess the potential effect of explicit knowledge on the ability to transfer sequence performance across conditions, the two groups were median split based on their recognition scores into a high explicit knowledge group ($n = 15$) and a low explicit knowledge group ($n = 13$). The difference in confidence ratings provided to the trained sequence and foil sequences in the low explicit knowledge group was much lower ($M = 1.58, SE = .67$) than participants in the high explicit knowledge group ($M = 11.42, SE = 1.37$). However, the amount of performance transfer exhibited in the low explicit knowledge group ($M = 4.95\%, SE = 2.00\%$)
similar to the transfer exhibited by the high explicit knowledge group ($M = 5.21\%, SE = 2.14\%$), $t < 1$, suggesting that sequence performance transfer was not driven by explicit knowledge.

**Discussion**

In both the Standard and Isolated perceptual training conditions, participants demonstrated a clear sequence-specific performance advantage for their repeated sequence, showing that they learned and performed the repeating sequence better than the non-sequence trials. During the transfer test when participants switched to the condition that used the unfamiliar presentation method, participants exhibited a significant drop in performance of their learned sequence even though they were performing the identical motor response sequence. Performance in the transfer condition was still better for the trained sequence than for novel foils, indicating that there was partial transfer of sequence knowledge when the amount of perceptual information on screen was modified. The expression of sequence knowledge in the transfer condition was roughly 25-30% despite maintaining the spatial compatibility and motor response characteristics across conditions. The lack of transferable sequence knowledge when the perceptual display was changed was much higher than would be expected if perceptual learning of the stimulus display is a separate component of the sequence representation that is not integrated along with the overall representation. These results provide evidence for the specificity of motor-sequence knowledge, and suggest that the integration of the components is crucial to models of implicit skill learning transfer.

A simple transfer model of overlapping components would predict more robust transfer because all motor action components were identical for training and test. The large cost in knowledge transfer suggests that this visuospatial information is not only learned, but that there
is also a component of integration between perceptual and motor components that is necessary to maintain for the maximum transfer of knowledge. These results support a model of performance transfer whereby there is integration across separate component processes that are operating during perceptual-motor sequence learning.

A sequence knowledge representation that consists of both separate component processes and integration across them is most consistent with the dual-system model of sequence learning put forward by Keele et al. (2003) and expanded upon recently by Abrahamse et al. (2010). In this integrative approach, the success of the sequence representation ultimately depends on how knowledge is stored. The two components of this dual system are the uni-dimensional and multi-dimensional components, which are learned and integrated simultaneously during implicit learning. The uni-dimensional components are defined as the individual aspects contained within the learning of a sequence, such as perception, motor affecter, etc., that are learned implicitly. The multi-dimensional components allow for the connections within and across the smaller dimensions, representing the integration process. Regardless, both play an equally important role during the representation of knowledge. This model suggests that the representation of knowledge depends upon how stimuli are processed and responded to during training.

Thus, the overlapping component theory of perceptual-motor sequence learning proposed here can be paralleled to the uni- and multi-dimensional idea in sequence representation proposed by Keele et al. (2003) and Abrahamse et al. (2010). The individual components are similar to the uni-dimensional items and the components integration through the overlapping of knowledge and simultaneous learning is similar to the multi-dimensional simultaneous representation of the overall network. This allows for a possible explanation as to why expression of sequence knowledge is so inhibited in similar conditions of transfer. If one aspect
of the perceptual information is changed, such as the arrangement or the amount of information, it drastically changes how the entire stimuli and response representation is processed and integrated. This may explain why only a fraction of sequence knowledge is expressed.

In addition to the visuospatial component that interrupted transfer across conditions, another potential component that may have led to a lack of transfer was the variance in response characteristics across conditions. Due to the cue velocity in the Isolated cue condition, participants were required to respond shortly after the cue entered the screen, making the interception response more sensitive to reaction time. Thus, while both conditions required participants to intercept the cue as it passed through the target zone, the velocity in the Isolated condition required responding more similar to a reaction time style response, as opposed to the more fluid interception responding in the Standard condition. If this variance in response characteristics became a learned component, it may have become integrated along with the overall sequence representation, and contributed towards the overall specificity of the representation.

Of note, participants in the Isolated condition also had significantly higher levels of explicit knowledge for their trained sequence, and slightly higher sequence-specific performance benefits at test. This increase in explicit knowledge and subsequent possible benefit to sequence performance stands in stark contrast to previous results with the SISL task (Sanchez & Reber, 2013), but is similar to effects seen in reaction time measures of sequence learning such as with the Serial Reaction Time task (Frensch & Miner, 1994). However, this explicit knowledge did not affect transfer of sequence performance in this condition, suggesting that the transfer capabilities are not dependent on explicit knowledge. Thus, the model of transfer proposed here is based on specificity in an implicit learning system.
Overall, the results suggest that practice produces knowledge that is very specific to what is trained. There was only partial transfer of this specific sequence knowledge across transfer test conditions that share only very slight differences, when more benefits from the practiced knowledge were expected. When an aspect of the perceptual response was manipulated, such as the amount of perceptual cues on the screen in this case, the changes led to dramatic reductions in performance of their trained sequence even while keeping the motor responses consistent. These results further support multiple components of sequence knowledge that together can be integrated to form specific procedural knowledge. However, these mechanisms may be partially expressed depending on the certain task demands. In the current study, the task manipulations were fairly similar across conditions, so the results of only partial transfer are surprising considering significant training does not necessarily always lead to expressible sequence knowledge across these similar conditions. Even with the known specificity of procedural learning, these results suggest there indeed might be some flexible knowledge in certain conditions of sequence learning. In general, when practicing forehands in tennis the motor-skill knowledge gained is very specific. However, maybe the mechanisms involved will help improve other similar and related motor skill mechanisms in the next practice. Extensive practice on forehands may help an athlete’s backhand technique in a minor capacity, but it probably helps less than desired, thus making extensive backhand practice equally important. Research on the specificity of other mechanisms of timing or perception of sequence learning would further address the questions of specificity. The specificity of motor and perceptual components again suggests that practice is needed for every mechanism in order to learn procedural knowledge, and that integration of all of these components is just as important. Ultimately, the results support the claim that one should practice what he or she wants to learn. When one minor
component is changed, the entire integrated representation is affected, leading to the inflexibility of implicitly learned knowledge to very similar contexts.
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Figure 1. SISL task in Standard and Isolated cue variants. In both versions of the task, the cues scroll down one of four columns towards four rings that are displayed in a spatially-compatible layout that correspond to the response locations on the keyboard (D,F,J,K). In both of the task variants above, only stimuli within the white space are visible to the participant. a) In the Standard version of the task, multiple cues are visible on the screen at a time. b) In the Isolated cue version of the task, only a single cue is visible at a time. This change is made by increasing the physical distance between the cues while also increasing the velocity the cues are scrolling at, so that the inter-stimulus timing between cues remains the same between conditions. Note that the cue with the dashed-outline in the grey area of the figure is not visible to the participant, but is being used to display how the distance between cues changes between conditions.
Figure 2. Sequence-specific performance advantage during training and test. Both the Standard and Isolated cue training conditions show a linear increase in sequence-specific performance improvements over training, with significantly more sequence-specific performance benefit expressed during test with the trained condition, compared to the transfer condition.
References


