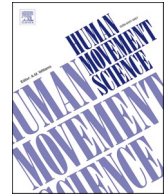




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Across-task binding: The development of a representation in learning a continuous movement sequence

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ABSTRACT

Across-task binding is defined as the stimulus/response of one task being linked to the response of another task. The purpose of the present experiment was to determine across-task binding in a continuous movement sequence task with an auditory task of high and low pitch tones and the development of a movement sequence representation. According to the two systems theory of sequence learning, we expected that the developed representation in the across-task binding context relies on the multi-dimensional system rather than on the unidimensional system which is restricted to a set of modules where each module processed information along one task/dimension. An inter-manual transfer design was used to disentangle the sequence representations. The mirror transfer test required the same pattern of muscle activation and joint angles (motor coordinates) in the contralateral limb as experienced during the acquisition phase, while in the non-mirror transfer test, the visual-spatial locations (spatial coordinates) of the target waveform were reinstated. The main finding was that consistently combining visual-spatial positions in a sequence and auditory dimensions such as the tone pitch does not rely on a multidimensional system as predicted by the two-systems theory.

1. Introduction

Across-task binding is defined as the stimulus of one task being linked to the stimulus/response of another task. If both tasks are consistently combined, an integrated representation will develop (e.g. Heuer, 1996; Röttger, Haider, Zhao, & Gaschler, 2019; Schmidtke & Heuer, 1997).

A theoretical approach that seems to account fairly well for at least some of the observed effects of across-task binding in a sequence representation is the two-system theory of sequence learning suggested by Keele, Ivry, Mayr, Hazeltine, and Heuer (2003). This model proposes that sequential learning can be viewed in terms of two distinct learning systems: one unidimensional and one multidimensional learning system (Curran & Keele, 1993). The unidimensional system is thought to be implicit and comprised of different input modules where each module is restricted to process information within a single dimension or modality. The associations within a single dimension (or module) are encapsulated, indicated by a lack of correlation between the two events. Further, the authors

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assumed that this learning system did not require attention. An example reported by Keele and colleagues is driving a car on a familiar street and listening to the car radio. The driver is able to make sense of two independent informational channels: visual-spatial information from the street to steer the car to keep the route and auditory information from the car radio for listening a song (Keele et al., 2003).

The multidimensional learning system shares explicit and implicit associations and develops associations/linkages/correlations between events from different modalities or dimensions through practice. These include, for example, the visual-spatial positions of the sequence task and features of the auditory dimension such as a tone pitch. In addition, attention is required because information of the environment is necessary to build the linkages across different tasks (Hazeltine, Ruthruff, & Remington, 2006; Röttger et al., 2019; Schumacher & Schwarb, 2009). The coincidence of the cross-dimensional modalities enhances the learning of movement sequences. For example, when initially learning waltzing, the sequence and the cadence of the dance steps ('one, two, three') is prescribed by the beat of the music. In this case, different modalities (auditory/motor) support the learning of the sequence of steps.

However, the two-systems theory does not provide any information about the modalities of the representations. The notion of modalities/coordinate systems in a sequence representation was refined as a result of a series of experiments (Shea, Kovacs, & Panzer, 2011, for an overview) and the Parallel Network Model proposed by Hikosaka et al. (1999). The core tenet of the theoretical model is that two representations develop in parallel (visual-spatial and motor representations). At the initial stage of learning, participants perform actions in a discrete, step-by-step manner by relying on the sensorimotor transformation for each action which is described by serial sensorimotor processes for individual actions. During this stage of learning, explicit knowledge related to the visual-spatial information of the sequence appears to be available to consciousness, and the attention requirements to perform the motor actions are high (e.g., Shea et al., 2011). With increasing practice, participants are able to perform the actions sequentially without relying on the inefficient step-by-step sensorimotor processes. Individuals become faster and more accurate in responding to the stimuli and perform the corresponding movements in a smoother, more fluent and continuous way (Bapi, Doya, & Harner, 2000; Hikosaka et al., 1999; Panzer, Krueger, Muehlbauer, Kovacs, & Shea, 2009; Sakai et al., 1998). At this stage of learning, sequence production primarily relies on motor information, whereas continuous visual control and attention requirements are reduced. Sequence production is implicit and became nearly automatic thereby making it less vulnerable to interfering tasks. Note, the serial sensorimotor processes for individual actions from the initial stage of learning are gradually replaced by parallel sequential processes.

Recent studies on a behavioral level using an inter-manual transfer design to disentangle the visual-spatial and the motor representation have provided empirical evidence that not only practice has an important role in the development of a visual-spatial and a motor representation. It appears that other factors play an important role in determining which of the two representations is the responsible coding scheme for sequence production (Clegg, DiGirolamo and Keele, 1998; Keele, Jennings, Jones, Caulton, & Cohen, 1995; Kovacs, Han, & Shea, 2009; Kovacs, Muehlbauer, & Shea, 2009; Park & Shea, 2005; Shea et al., 2011 for an overview, Verwey & Clegg, 2005). Named in the literature for instance are sequence complexity (number of elements, number of reversals in the sequence and/or sequence duration) (Kovacs, Muehlbauer, & Shea, 2009), and the availability of concurrent visual feedback during sequence execution (Kovacs, Boyle, Gruetzmacher, & Shea, 2010; Leinen, Shea, & Panzer, 2015; Panzer et al., 2009; Shea et al., 2011).

For instance, Leinen et al. (2015) had participants practice a sequence of extension flexion movements for 99 trials during one practice session. The sequence involved five reversals and the movement duration was 2000 ms. In one condition concurrent visual feedback during sequence execution was available, while this information was withheld during movement production for the other condition. Afterwards, the participants were administered a retention test and two effector transfer tests. The mirror effector transfer test required the same pattern of muscle activation and limb joint angles as required during acquisition. The non-mirror transfer test required individuals to perform movements to the same visual-spatial locations as experienced during acquisition. The results indicated that when concurrent visual information was available, transfer performance was superior in the non-mirror transfer test. However, when no concurrent visual information was available, performance on the mirror transfer test was superior where the motor coordinates had been reinstated. These results indicated that individuals use the most salient information for response production.

The current unidimensional vs. multidimensional sequence learning system of Keele et al. (2003) differ in attention demands and are linked to implicit vs. explicit sequence knowledge. However, in the past, researchers have sought model tasks to analyze across-task binding and sequence learning. In this context, across-task binding is predominantly studied with a visual-manual key-press sequence and an auditory-vocal task (e.g., Gaschler, Zhao, Röttger, Panzer, & Haider, 2019; Haider, Eberhardt, Esser, & Rose, 2014; Röttger et al., 2019; Röttger, Zhao, Gaschler, & Haider, 2021; Schmidtke & Heuer, 1997). One inference drawn from these experiments is that participants seem to develop stimulus-stimulus associations (see Haider et al., 2014). Given that the stimuli are linked to the responses, a stimulus-stimulus link indirectly also activates the response of the other task (see also Hommel, 2004; Marcus, Karatekin, & Markiewicz, 2006; Waszak, 2010). Further, research on across-task binding is predominantly aimed in the context of implicit sequence learning and multi-tasking (Schmidtke & Heuer, 1997; Schumacher & Schwarb, 2009), and to a lesser extent on the provided information during response production and the development of an integrated representation. Here we employ the transfer phase approach developed in motor sequence learning studies (Shea et al., 2011). We test whether and how auditory stimuli of a second task become integrated in the movement sequence representation. The stimulus from a different modality might be linked/bound to the movement sequence representation (see also Hommel, 2004).

Across-task binding is widely recognized in the cognitive psychology literature (Hommel, 2004; Röttger et al., 2019; Schmidtke & Heuer, 1997; Waszak, 2010) but only rarely followed in the area of motor learning and the development of a movement sequence representation. The primary goal of the present experiment was to determine the extent to which individuals can develop associations/linkages (across-task binding) between events from different modalities to a movement sequence representation. Our hypotheses based on previous results from Leinen et al. (2015) according to which salient visual information encourages the system to use the visual-spatial coordinates for response execution and on the theoretical assumption that representations in both coordinate systems

develop in parallel (Hikosaka et al., 1999). We hypothesized that individuals, who are provided with visual feedback about the limb position during sequence execution in the transfer test will perform the non-mirror transfer test better than the mirror transfer test. This will show that the visual-spatial coordinate system is the prime determiner for sequence execution. However, if visual feedback will be withheld, transfer performance in the mirror transfer test is superior. This will indicate that the motor coordinate system is primarily responsible for response execution.

If across-task binding occurs and individuals developed a linkage between events from different modalities, correlations between the two events should be observable. A change or dispersal in one task would result in a dysfunctional across-task binding effect accompanied by interference and reduced correlations between the two tasks. Related to this, it is relevant if the interference effect is larger on the non-mirror or the mirror transfer test. According to the two-systems theory (Keele et al., 2003), the multidimensional system attempts to integrate the stimuli from both tasks at the cost of attention. Further, the Hikosaka et al. (1999) proposal suggests that the attentional demands at the visual-spatial representation are high. Therefore, we hypothesized that non-mirror transfer performance will be deteriorated when the spatial positions of the stimuli are changed, especially when visual information is provided during response production. The correlations between the two events should decrease. This pattern of results will provide valuable information about the debate of the loosely defined terms of modalities or dimensions (Röttger et al., 2019) in the ‘two-systems theory of sequence learning’ proposed by Keele et al. (2003).

2. Methods

2.1. Participants

Undergraduate students participated in the experiment for course credit. The number of participants was a priori calculated by G*Power (Faul, Erdfelder, Lang, & Buchner, 2007) using the power of 80%, a given $\alpha = 0.05$ and the effect size $f = 0.58$ (Cohen, 1988) as a realistic estimate from the Röttger et al. (2019) Experiment 4. The calculation revealed a sample size of $N = 26$ participants (mean age = 22.38, SD = 3.18, female: $n = 11$, male: $n = 15$). The participants had no prior experience with the experimental tasks and were not aware of the specific purpose of the study. Prior to the experiment, all participants completed the Edinburgh Handedness Inventory (Oldfield, 1971). All were right-handed dominant. An informed consent to the procedure of the study according to the declaration of Helsinki was provided and signed prior to participation.

2.2. Apparatus

The apparatus consisted of two horizontal levers (42 cm long) supported at proximal end by a vertical axle that turned almost frictionless in a ball-bearing support. The supports were fixed on the left and right sides of the table, allowing the lever to move in the horizontal plane over the table. A vertical handle was fixed at the distal end of each lever. The position of the handle could be adjusted so that, when the participant rested their forearm on the lever, their elbow aligned exactly over the axis of rotation and they could comfortably grasp the handle (from above). A potentiometer (Midori Orange Pot CP-45H; linearity $\pm 0.4\%$) was attached to the lower end of the axis of each lever to record the position of the lever. The output was sampled at 1000 Hz. The potentiometer data were used to provide the lever position information to the participant and stored for later analysis. The experiment was programmed with MatLab® R2021a software from MathWorks® (The MathWorks, Inc., Natick, MA). A wooden cover was placed over the table to prevent individuals from seeing the lever and their arm.

A video projector (temporal resolution 100 Hz; spatial resolution 1920×1080) presented the goal waveform (see Fig. 1A) on the wall facing the participant. It also displayed the position of the moving hand and feedback. The participants were seated at about 2 m from the wall and a 2×2 m image was projected in front of them on the wall.

For the tone discrimination task, auditory stimuli (high and low pitch tones) were presented by two loudspeakers (Creative A40) placed in front of a table at about 70 cm from the participants. The high pitch tone had a frequency of 1000 Hz and a duration of 60 ms,

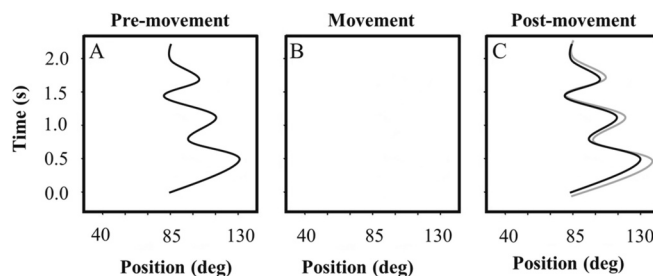


Fig. 1. Illustration of the visual information of the movement sequence during a complete trial of a group who was not provided with visual feedback during sequence execution. (A) The left display illustrates the target waveform prior to movement onset. (B) The middle display illustrates the movement execution phase where the visual information of the target waveform and cursor was withdrawn. (C) The right display illustrates the visual feedback after movement production that included a superimposition of the target waveform (black) and the participant's produced waveform (grey).

while the low pitch tone had a frequency of 300 Hz and 60 ms duration. On a scale between 1 and 10, the volume level of the loudspeakers was set to 7. The frequency, duration, and volume levels were tested before the actual experiment in a pilot study. The two tones were triggered by an Arduino microcontroller. To reduce the interaction with other software that affects the timing of the computer all software and supports running in the background of the computer were closed and all other USB devices not used were disconnected. The accuracy of the auditory responses was noted by the experimenter. Further, the responses were video-taped to control the accuracy.

2.3. Experimental group, task and procedure

The experiment was conducted in a quiet and dimmed laboratory room. After entering the laboratory, the participants were seated in a chair facing the table and the apparatus which was adjusted so that the participants' lower arm was at approximately an 85-degree angle to the upper arm at the starting position. Instructions were presented on a paper sheet informing participants of how to perform the two tasks. At the beginning of each trial, the goal waveform was displayed (Fig. 1A), and participants were asked to move the lever to the starting position (1° area at the beginning of the goal waveform). The goal waveform (a spatial-temporal waveform pattern of 2000 ms duration with five reversal points) was created by summing three sine waves with different periods and amplitudes. The amplitudes of the goal waveform ranged between 0° to 45° from the start position. After positioning the lever in the start position (elbow joint less than 10°) a random fore period (2–5 s in 0.5 s intervals) was initiated prior to the initiation of a tone (600 Hz; 60 ms). This tone signaled the participant to begin their response. The lever movement triggered data collection. If the participant moved from the start position prior to presentation of the tone, the participant was required to move back to the start position for 1 s before the tone was presented again. This ensured that the participants started in the correct position on the criterion sequence but could initiate their response when they felt ready.

The participants were instructed to move the lever with their arm through a sequential pattern of extension–flexion movements (5 reversals; changing the movement direction from extension to flexion or vice versa) in an attempt to produce the goal waveform displayed prior to sequence execution in front of them on the wall. They were asked to be as accurately and continuously as possible (Fig. 1A). Approximately 5 s following the completion of the participant's movement the goal waveform (black colour) and the produced movement pattern (grey colour) were overlaid in the display and projected on the wall for 10 s (Fig. 1C). Furthermore, the root mean square error (RMSE) was displayed. Participants were told that they should decrease the RMSE error to increase their performance. The time interval of 10 s was chosen to ensure that participants had enough time to process feedback information. Between every trial, an interval of 10 s was required and after every 10th trial a break of 1 min was introduced. This was done to induce micro-offline gains (Bönstrup et al., 2019) to increase the development of an integrated representation. During these time intervals, participants were required to rest the lever at the start position.

Prior to entering the testing room participants were randomly assigned to one of two acquisition conditions: a visual information available (VIA) and a visual information not available (VINA) condition. In the VIA condition, the participant was able to view the cursor indicating the position of their limb during sequence production. In the VINA condition, any visual information was withdrawn (Fig. 1B). The withholding of visual information during response execution increased the likelihood to code the sequence in a motor coordinate system. Note that prior to the initiation of the response and following sequence execution, both groups were provided identical information in the visual displays. The post-response display, superimposed target, and produced waveforms, and the root mean square error were considered knowledge of result (KR).

Prior to acquisition of the movement sequence task, all participants were familiarized with the tone discrimination task. They were required to discriminate in 20 trials between high and low pitch tones, without any movements (10 trials high, 10 trials low tone, order randomized). Acquisition practice under VIA and VINA conditions consisted of 10 blocks of 10 trials each.

To control effects of tone pitch, for half of the participants in each acquisition condition the low pitch tone was positioned at the second reversal point where a flexion movement was required. The high pitch tone was positioned at the fifth reversal point where an extension movement was required. For the other half the assignment of the tones was reversed. Note that a verbal “high” vs. “low” response to the tone pitches was required during sequence execution. An error was marked if individuals (a) did not respond, (b) respond too late when the sequence task terminated, or (c) respond in the wrong order.

Approximately 24 h after the completion of the acquisition phase, participants from each acquisition condition (VIA and VINA) returned for a retention test. All groups performed two retention tests under the same conditions (right hand and same goal waveform) as experienced during acquisition except that (KR) was not provided as it had been during acquisition. In one test the order of the pitch tones was the same in the other the order was changed.

After the retention tests, the participants were administered a “mirror” and “non-mirror” contra-lateral transfer tests with the tone discrimination task. The two transfer tests (12 trials each) were performed with the contralateral limb (order counter-balanced). In the mirror transfer test, the target waveform was mirrored on the vertical axis so that the same pattern of homologous muscle activation and limb joint angles were required as during acquisition and on the retention test. In the non-mirror transfer test, the visual-spatial locations of the target waveform used during acquisition and experienced during retention testing were reinstated but the participant used the contralateral limb. Note that in the mirror transfer test, the motor coordinates used during acquisition were reinstated while the visual-spatial coordinates were changed. Alternatively, in the non-mirror transfer test, the visual-spatial coordinates used during acquisition were reinstated but the motor coordinates were changed. Both transfer tests were conducted under the same conditions compared to acquisition. Both transfer tests were also administered in a variant in which the spatial position of the ‘high’ and ‘low’ pitch tones was switched (order counter balanced). Note, participants were instructed to perform both tasks with equal priority.

2.4. Data analysis and statistics

Data analysis was performed using MatLab (Mathworks, Natick, MA, R2021a). The individual trial time series were used to compute lever displacement. To reduce noise in the data, the angular displacement time series was filtered with a low-pass filter (2nd order dual-pass Butterworth filter) with a cutoff-frequency of 10 Hz. The RMSE was computed as an estimate of the performance error in achieving the goal movement pattern. RMSE incorporates both the variability and bias of the performed movement pattern. Additionally, RMSE captures errors in both amplitude and time. RMSE was computed by the quadratic mean difference between the criterion and the actual movement pattern at each data point in the time series. The final step in computing RMSE was to determine the square root of the mean of the squared differences. Values of RMSE for individual trials were then averaged to yield a global estimate of RMSE for each block. The accuracy of the tone discrimination task was evaluated by the percentage of correctly identified verbal responses (%correct). For this, the number of correct responses were divided by the total number of trials in a block and multiplied by 100. Finally, the correlations between the RMSE and the %correct at the transfer tests were calculated by Pearson's product moment correlations. To compare the correlation coefficients the values were Fishers' z-transformed. Statistical analyses were computed with SPSS for Windows Version 29.0 (IBM Corp., Armonk, NY, USA). Adjustments were made for violations of homogeneity and sphericity (Winer, 1971). To determine statistical significance an alpha level of 5% was used. Partial eta square (η_p^2) is the effect size reported for all significant effects (Cohen, 1988). Post-hoc comparisons of significant main effects were computed using the Duncan multiple range tests for within-subject effects. Detailed analysis of significant main effects, interaction effects, and post-hoc tests was followed by Bonferroni-corrected pairwise comparisons when necessary.

3. Results

Fig. 2 provides the mean RMSE and the standard error of the means (SEM) across the different conditions during acquisition and retention (A) and for the transfer tests (B).

Acquisition: Mean RMSE was analyzed in a 2 (Condition: VIA, VINA) X 10 (Block: 1–10) ANOVA with repeated measures on the last factor. The analysis indicated a Condition by Block interaction, $F(9,216) = 4.36, p = .003, \eta_p^2 = 0.15$. Simple main effect analysis for Condition across Group indicated that the VIA participants decreased the RMSE throughout Block 4 and then leveled off, while the VINA participants decreased the RMSE until Block 7. This suggested that the VIA participants decreased the RMSE faster than the VINA participants. In addition, the main effect of block, $F(9,216) = 51.13, p < .001, \eta_p^2 = 0.68$ reached significance. The main effect of condition was also significant, $F(1,24) = 16.99, p < .001, \eta_p^2 = 0.42$, with smaller RMSE for the VIA condition where visual information about the position of the limb during sequence execution was available.

3.1. Retention and transfer tests

An example of the individual performance of one randomly chosen participant from each group on the transfer tests is provided in Fig. 3. Depicted are the target wave form in black and the 12 produced waveforms in each transfer test in grey. For the individual of the VINA condition the variability of the produced waveforms on the non-mirror transfer tests (see Fig. 3F and H) were apparently higher compared to the mirror transfer tests (see Fig. 3E and G). This pattern of result did not occur for the participant in the VIA condition (see Fig. 3A to D).

RMSE, Retention tests: The 2 (Condition: VIA, VINA) x 2 (Tone position: not changed, changed) ANOVA with repeated measures on the last factor indicated a significant main effect of Condition, $F(1,24) = 24.41, p < .001, \eta_p^2 = 0.50$. The RMSE was higher for participants in the VINA condition. There was neither a Condition x Tone position interaction, $F(1,24) = 2.33, p > .05$, nor a main effect Tone position, $F(1,24) = 1.29, p > .05$.

RMSE, Transfer tests: The 2 (Condition: VIA, VINA) x 2 (Test: mirror, non-mirror) x 2 (Tone position: not changed, changed)

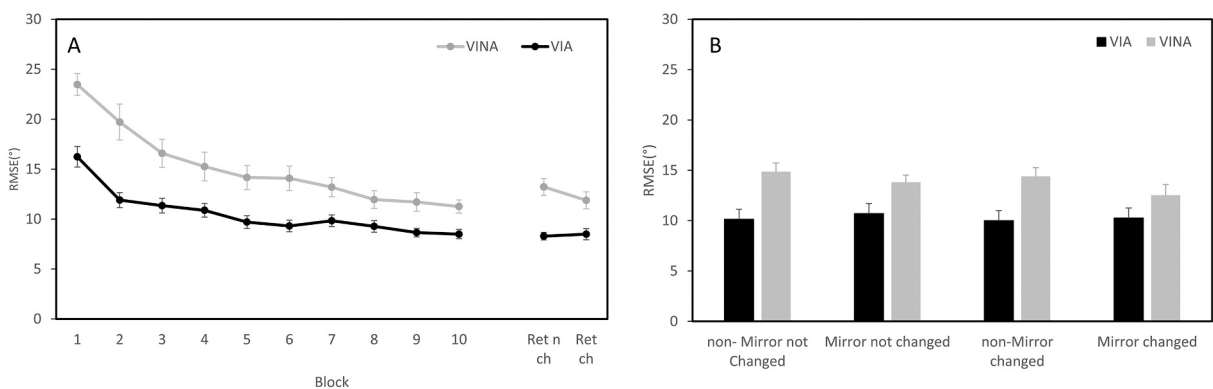


Fig. 2. Mean values of the RMSE (°) and the standard error of the mean (SE) of the RMSE during acquisition, retention (A) and during the (B) transfer tests. Ret n ch is the acronym for retention Test tone positions not changed and Ret ch for tone positions changed.

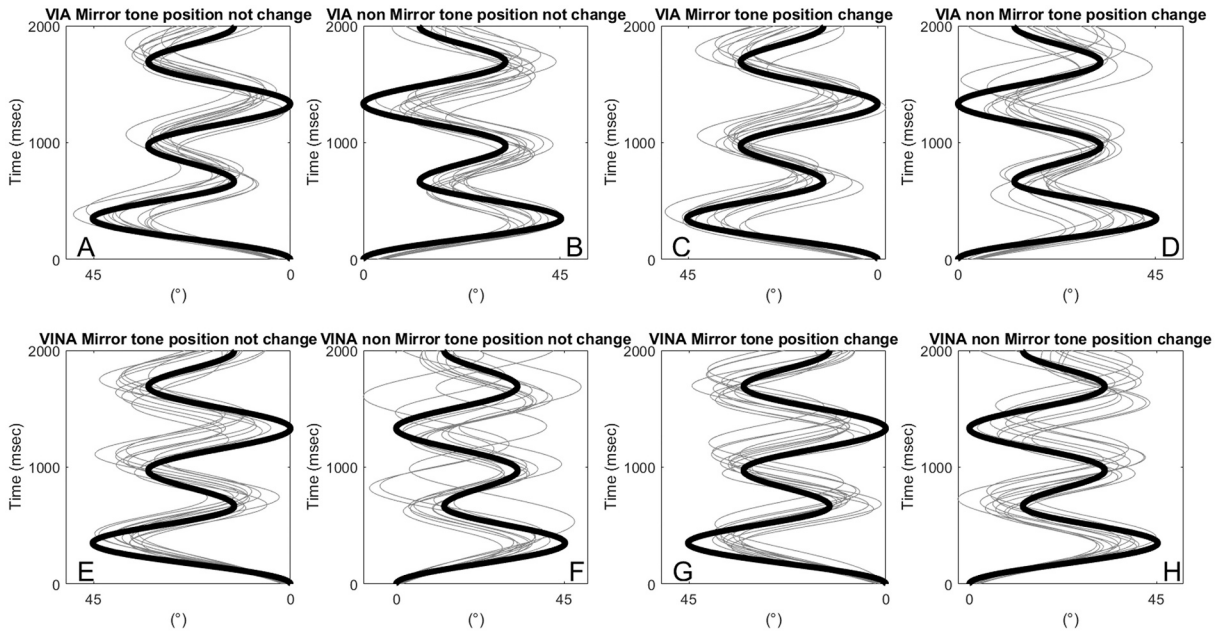


Fig. 3. Examples of performance for one participant in the VIA condition (A, B, C, D), and the VINA condition (E, F, G, H), on the mirror (A, C, E, G), and non-mirror (B, D, F, H) transfer tests.

ANOVA with repeated measures on the last two factors indicated a Condition by Test interaction, $F(1,24) = 5.89, p < .05, \eta_p^2 = 0.20$. The decomposition of the interaction with a simple main effect analysis for Condition across Test revealed that RMSE for the VINA group was lower on the mirror transfer tests ($M = 13.18^\circ, SEM = 0.64^\circ$) compared to the non-mirror transfer tests ($M = 14.64^\circ, SEM = 0.59^\circ$). The main effect of Condition reached significance, $F(1,24) = 17.02, p < .001, \eta_p^2 = 0.42$. RMSE was lower for the VIA condition compared to the VINA condition. There was neither a three-way interaction Condition x Test x Tone position, $F(1,24) = 0.07, p > .05$, a two-way interaction Condition x Tone position, $F(1,24) = 0.96, p > .05$, or Test x Tone position, $F(1,24) = 0.34, p > .05$, nor a main effect of Test, $F(1,24) = 1.84, p > .05$, or Tone position, $F(1,24) = 3.72, p > .05$.

Percent correct, Transfer tests: Fig. 4 provides the mean %correct responses of the tone discrimination task and the standard

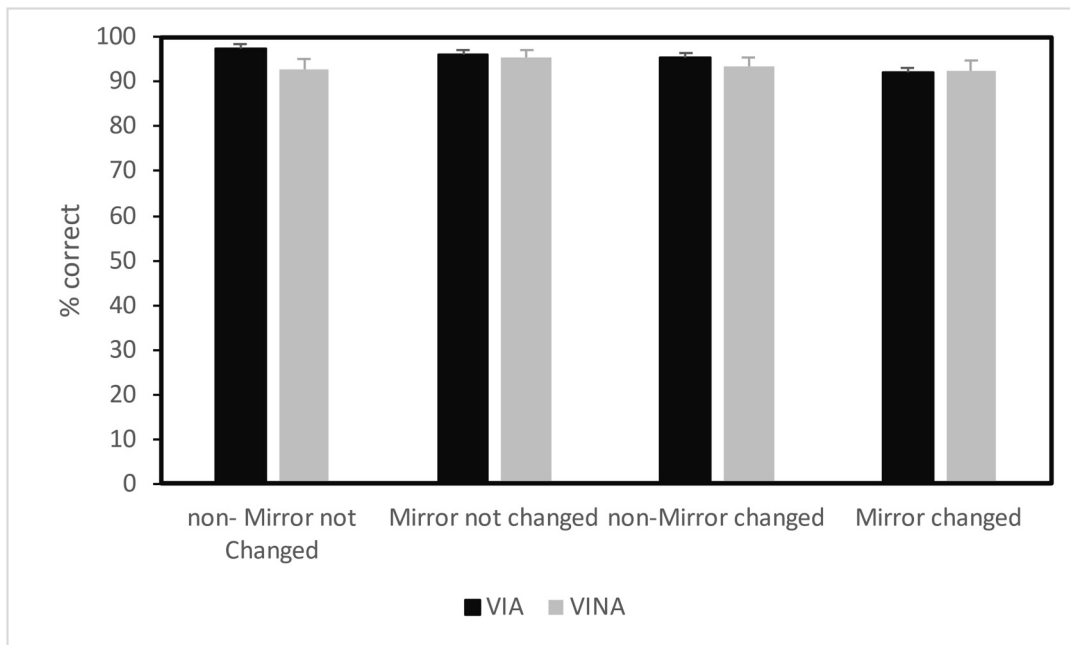


Fig. 4. Illustration of the mean and the SE of the mean of the % correct answers of the high and low pitch tones during the transfer tests.

error of the means (SEM) across the different conditions for the transfer tests.

The 2 (Condition: VIA, VINA) x 2 (Test: mirror, non-mirror) x 2 (Tone position: not changed, changed) ANOVA with repeated measures on the last two factors failed to detect a three-way interaction Condition x Test x Tone position, $F(1,24) = 0.33, p > .05$. In addition, the two-way interactions Condition x Tone position, $F(1,24) = 1.08, p > .05$, Test x Tone position, $F(1,24) = 0.34, p > .05$, Test x Condition, $F(1,24) = 1.57, p > .05$, and the main effects Test, $F(1,24) = 1.05, p > .05$, Condition, $F(1,24) = 0.07, p > .05$, and Tone position, $F(1,24) = 2.25, p > .05$, were not significant. The mean %correct responses for the two groups at each transfer test was above 90%.

3.2. Correlations between RMSE and %correct for the transfer test

To determine the associations/linkages (across-task binding) between the events from different modalities to a movement sequence representation, Pearson's product-moment correlations between the RMSE and the %correct were conducted. Table 1 illustrates the relationship between the RMSE and the %correct responses for the two groups at the transfer tests.

Pearson's product-moment correlations portrayed in Table 1 indicated no significant correlations. Further, a supplemental analysis was performed that contrasted the product-moment correlations of the mirror and non-mirror transfer tests for the non-changed and changed tone positions in the VINA and VIA condition. As illustrated in Fig. 5, the Fishers' z-transformed correlations and the 95% confidence intervals indicated that the intervals for the mirror and non-mirror transfer tests across the two groups overlap. This suggested that the correlations were not statistically different.

4. Discussion

The experiment was designed to determine the role of visual information and the degree to which individuals can develop associations/linkages (across-task binding) between events from different modalities to a movement sequence representation for a continuous movement sequence. As in the Leinen et al. (2015) experiment, and in accordance with the Parallel Network Model (Hikosaka et al., 1999), we hypothesized that withholding visual information during sequence execution would increase the likelihood that performance is superior at the mirror transfer test where the motor coordinates remained the same as during acquisition. However, providing visual information during sequence production would increase the likelihood that the non-mirror transfer performance would be better when the visual-spatial representation is primarily responsible for response production. According to the two-systems theory of sequence learning from Keele et al. (2003), it was expected that in cross-dimensional sequence learning the multi-dimensional system is primarily involved. Therefore, linkages across visual-spatial positions and auditory events such as tone pitches will be developed which results in across-task binding. Further, we predicted if across-task binding occurred, and individuals would have developed a linkage between events from different modalities a change or dispersal in one task would result in a dysfunctional across-task binding effect. The dysfunctional across-task binding effect should be accompanied by a reduced correlation between the two tasks. This should be observable at the non-mirror transfer test, because of the attention requirements of the multidimensional system and the visual-spatial representation (see Hikosaka et al., 1999; Keele et al., 2003).

The findings of the present experiment indicated that during acquisition the VIA and the VINA group increased their performance. However, the individuals of the VIA group outperformed those of the VINA group. The performance on the retention and transfer tests was superior for the VIA group who were provided with visual information about the position of the limb compared to the VINA group which this information was withheld. These results are in line with the findings provided by Kovacs et al. (2010) who demonstrated in an experiment that withholding visual feedback deteriorates sequence performance compared to a condition where visual feedback was provided during sequence execution (see also Leinen et al., 2015). These results are also consistent with previous findings using aiming movements where individuals search for visual information to reduce the performance error (Elliott, Chua, Pollock, & Lyons, 1995). Performance for individuals at the VINA group were superior at the mirror transfer test compared to the non-mirror transfer test irrespective of whether the tone positions were changed or not. This suggests that utilizing the same patterns of flexion/extension movements, muscle activation, and joint angles in the transfer tests compared to the acquisition lead to better mirror transfer performance than when these characteristics are changed in the non-mirror transfer test where the visual-spatial locations stayed the same compared to the acquisition. This finding is partially consistent with our initial hypothesis and replicated previous results from Leinen et al. (2015) that withholding visual information favored the development of a motor representation where the motor coordinate system is primarily responsible for sequence execution.

Furthermore, changing the spatial tone positions in the transfer tests did not result in impaired transfer performance neither in the VIA group, nor in the VINA group. The Fishers z-transformed correlations across the transfer tests where the spatial positions of the tones were changed were not significantly different from those where the spatial tone positions were not changed. Therefore, the initial

Table 1
The correlation coefficients and the *p*-values for the two groups across the transfer tests.

Group	Non-Mirror not changed	Mirror not changed	Non-Mirror changed	Mirror changed
VINA	$r = 0.141$ $p = .645$	$r = -0.517$ $p = .071$	$r = 0.271$ $p = .371$	$r = -0.021$ $p = .945$
VIA	$r = 0.166$ $p = .587$	$r = -0.195$ $p = .523$	$r = 0.305$ $p = .311$	$r = 0.444$ $p = .128$

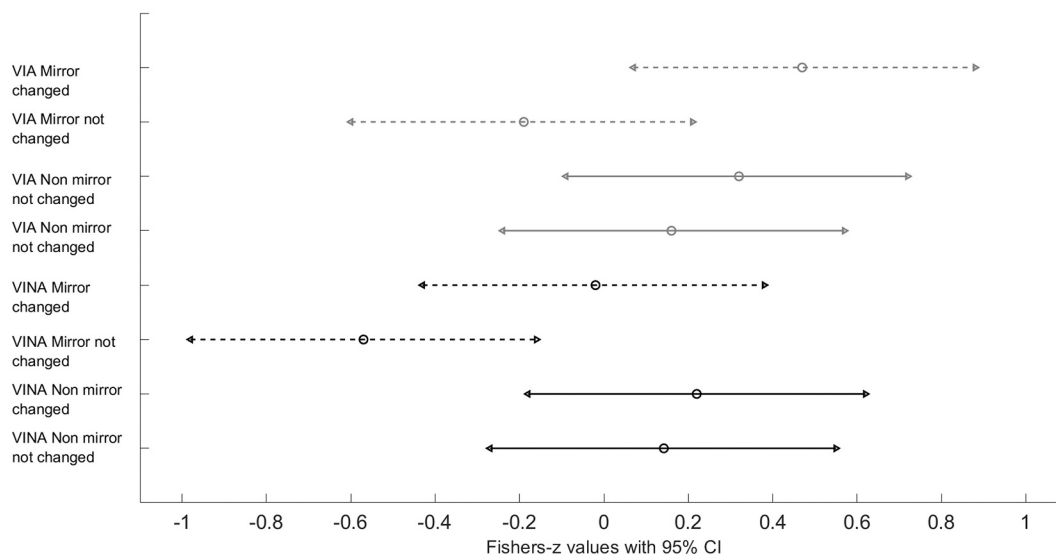


Fig. 5. The mean Fishers-z values and the 95% confidence interval (CI) of the different groups and conditions during the transfer test. The solid lines illustrated the non-mirror transfer performance and the dotted lines the mirror transfer performance.

hypothesis of the dysfunctional across-task bind effect following the changed tone positions is not supported. In terms of the auditory task, individuals at the VIA and the VINA group performed over 90% correct responses across the four transfer tests without any significant performance differences across the transfer tests.

4.1. Two-systems theory

The two-systems theory of sequence learning (Keele et al., 2003), discussed earlier in this article proposes that two distinct learning systems contribute to sequence learning: a unidimensional and a multidimensional one. The distinction implies that learning in a unidimensional system occurs in different input modules. Each module is limited to information of a single dimension (e.g., visual-spatial or auditory information) and associated with a lack of correlation between different events or dimensions. However, the multidimensional system develops linkages between different dimensions accompanied by a correlation between the events. In the present experiment, the results are in contrast to our initial hypotheses that during practice linkages across the visual-spatial positions and the tone pitches were developed. As opposed to the two-systems theory from Keele et al. (2003) this experiment demonstrates that consistently combining visual-spatial positions in a continuous sequence and auditory information such as the tone pitch does not rely on a multidimensional system. Even though the stimuli of the tone discrimination task were predictable in a repeating continuous movement sequence task, across-task binding was not observed within a visual-spatial or a motor representation. This provided some empirical evidence that the terms dimensions/modalities in the two-systems theory (Keele et al., 2003) do not refer to different codes/representations in a continuous movement sequence. Further, the failure to find meaningful correlations between the movement sequence task and the discrimination task and the high percentage of correct responses of the tone pitches can be attributed to the development of a visual-spatial and a motor representation that has occurred within the unidimensional system. According to the idea of the unidimensional system, visual-spatial and motor sequence information of a continuous movement sequence task is not linked to the auditory information of the tone task. Sequence information and the auditory information of both tasks are processed in two independent streams/modules (Keele et al., 2003; Röttger et al., 2019). Even then, when the spatial positions of the tones were changed, interference was not observed. This finding is in contrast with the consideration suggested by Broeker et al. (2017). They proposed that prediction facilitated sequence learning. Changing the arrangement of the predictive relationships impaired the performance, especially when elements of the first task based on elements of the second task. One can argue that the lack of the correlations was due to the low amount of practice. However, in the current study, we insert rest intervals from 10 s between every trial and after every 10th trial a rest period of 1 min to strengthen micro-offline learning to support the development of a stable representation (see Bönstrup et al., 2019; Conessa, Debarnot, Siegler, & Boutin, 2023).

Further, the model proposed by Keele et al. (2003) was developed largely based on findings from a serial reaction time (SRT) task linked to an auditory task (Haider et al., 2014; Schmidtke & Heuer, 1997). The SRT task was originally devised to test implicit sequence learning (Nissen & Bullemer, 1987). In this task, individuals were required to react to visual presented stimuli by pressing a key as quickly as possible. When the stimuli were presented in a repeated order, with increasing practice individuals start to anticipate the upcoming stimulus. In the cross-dimension task experiments, the temporal position of the secondary auditory task was at the interval between the response and the onset of the next stimulus (Hsiao & Reber, 2001; Shin & Ivry, 2002). As Keele et al. (2003) pointed already out that pairing different dimensions from two tasks, the linkages at the multidimensional system can be seen as a kind of classic conditioning (see Adams, 1987 for a historical review). In this context, two stimuli of different types were constantly paired and

shaped the behavior in way that the tone acted as an unconditioned stimulus which occurred shortly before the motor response (key-press). Paring the auditory stimulus consistently in temporal contiguity to the motor response supports the linkages in the multidimensional system. The 'classic conditioning' hypothesis from Keele et al. (2003) is also supported by some experimental observations from Shin and Ivry (2002; see also Koch and Hoffmann, 2000). Shin and Ivry (2002) were interested to determine the extent of different time intervals between response and stimulus in a SRT task to induce contiguity. According to the conditioning literature, the result from their experiment provided evidence that sequence learning was superior when the time interval between response and stimuli was short. This led the researchers to conclude that the temporal pattern between successive events in a SRT task was accompanied by sequence learning.

According to Shea et al. (2011) the task in the current experiment is a continuous movement sequence that required individuals to perform a precise execution of a template by a sequence of flexion extension movements (see, Gaschler et al., 2019; Leinen et al., 2015). The auditory discrimination task was positioned at the reversal points of the ongoing movement sequence where performers had to decelerate and accelerate the movement. Originally, classical conditioning proposed that a short time interval between the two stimuli is necessary to trigger the response. In the task of the current experiment both stimuli coincide (see also Smiley-Oyen & Worringham, 2001 for aiming movements). Thus, this factor could also account for the absence of the correlations and across-task binding between the two tasks.

The present results are also consistent with previous findings reported in the implicit sequence learning literature. A repeatedly investigated issue in implicit learning is related to the question if implicit learning requires attention (e.g. Curran & Keele, 1993). Nissen and Bullemer (1987) instructed individuals to learn an implicit SRT task under single-task (only the SRT task) and dual-task conditions (the SRT task and a tone counting task). In context of the dual-task condition, performance of the sequence task deteriorated. The reduced sequence performance in the dual-task condition led the researchers to conclude that implicit sequence learning requires attention. To determine if dual-task interference in implicit sequence learning caused by specific interference effects such as the temporal placement of a secondary tone counting task relative to the stimuli of the sequence and not a lack of general capacity, Frensch, Buchner, and Lin (1994) conducted a series of experiments. The main findings revealed that sequence learning was less deteriorated when the tones and the stimuli of the sequence occurred simultaneously. This indicated that specific interference effects are co-responsible for the decline in dual-task performance in implicit sequence learning and not the lack of capacity in general (Schmidtke & Heuer, 1997).

4.2. Parallel network model

As in the Leinen et al. (2015) experiment, the results of the present experiment are in some instances consistent with the Parallel Network Model (Hikosaka et al., 1999). As discussed earlier, the core tenet of the model is that representations based on visual-spatial and motor coordinates and both representations develop in parallel. Early in practice, the visual-spatial representation is primarily responsible for sequence execution while later in practice the motor representation becomes dominant for response production. However, by taking a different perspective of the Parallel Network Model, one can argue that individuals have access to both representations (Keele et al., 2003; Kurata & Hoshi, 2002) and the effectiveness of the transfer performance depends on the availability of salient information during sequence production. The VINA individuals had only access to motor information during sequence production. Therefore, it seems not astonishing that performance at the transfer test which required the same pattern of muscle activation and limb joint angles with the unpracticed limb as required during acquisition was superior compared to the non-mirror transfer test where this code was invalid.

A further empirical indication in favor that sequence information is processed in the unidimensional system is that transfer performance is not hampered when the spatial positions of the tones changed. This was expected if the link between the two tasks is only partial and shared not all events (Hommel, 2004; Keele et al., 2003). Especially interesting was the finding for the mirror transfer test at the VINA individuals where the transfer performance was superior compared to the non-mirror transfer performance. The change of the spatial positions of the tones required not a change of the movement directions. For example, at the mirror transfer test at reversal point two still a flexion movement was required and at reversal point five an extension movement. However, the location of the high and low pitch tones was different. The different locations of the tones hampered not the mirror transfer performance at the VINA group and seemed not relevant in a continuous movement sequence task using spatially defined responses (see also Hommel, 2004) where the motor coordinates (achieved joint angles, sequence of activation patterns of agonist/antagonist muscles) are primarily responsible for sequence execution. Additionally, this is underlined by the individual data illustrated in Fig. 3E to H. The variability of the two mirror transfers was less compared to the two non-mirror transfer tests. This indicated a more stable sequence production even if the positions of the tones were changed. The finding that the change of the spatial positions is not disruptive for sequence execution where the motor coordinates were primarily responsible for sequence production is also in line with the assumptions of the two-systems theory (Keele et al., 2003) and the Parallel Network Model (Hikosaka et al., 1999). According to these theories the unidimensional system and the motor representation require less attention.

The results of the mirror transfer test for the VINA individuals are also consistent with previous findings reported by Pfeifer, Panzer, and Shea (2022). In this experimental set-up, with the same movement sequence task without concurrent visual information during sequence production researchers introduced a dual-probe-task, because they were interested about the attentional demands of a sequence representation. The findings demonstrated that mirror transfer performance following one day of practice was superior compared to the non-mirror transfer performance. As other researchers note (Röttger et al., 2019; Röttger et al., 2021) that across-task binding induced dual-task performance effects the present finding provided some circumstantial evidence that the motor representation is less vulnerable against dual-task interference (see also Pfeifer et al., 2022).

5. Conclusion

In the current experiment we investigated across-task binding in a continuous movement sequence task with an auditory task of high and low pitch tones and the development of a movement sequence representation. To date, we disentangled the representation in a visual-spatial and a motor coding system by an inter-manual transfer design. According to the two-systems theory of sequence learning we expected the developed representation in the across-task binding context relies on the multi-dimensional system. The main finding was that consistently combining visual-spatial positions in a sequence and auditory dimensions such as the tone pitch does not rely on a multidimensional system as predicted by the two-systems theory. The failure to find meaningful correlations can be attributed to the development of a visual-spatial and a motor representation for the movement sequence and an auditory representation for the discrimination task that has occurred within the unidimensional system.

There is a limitation of the current experiment with regard to the multidimensional system and the idea of the ‘classic conditioning’ hypothesis proposed by Keele et al. (2003). In this context it is an open issue to know whether across-task binding is caused by consistently pairing the auditory stimulus with temporal contiguity to the motor sequence response to support the linkages at the multidimensional system. While the factor temporal position of the tone discrimination task in a continuous movement sequence is not directly studied in the current experiment the present results lay the groundwork for additional investigations like the stimulus onset asynchrony.

Ethics and consent

All procedures performed in the current experiment were in accordance with the ethical standards of the institutional (Universität des Saarlandes, Ethikkommission der Fakultät für Empirische Humanwissenschaften und Wirtschaftswissenschaften 18–08) and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. All participants gave written informed consent.

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CRediT authorship contribution statement

Stefan Panzer: Conceptualization, Funding acquisition, Methodology, Project administration, Software, Writing – original draft. **Christina Pfeifer:** Investigation, Visualization, Writing – review & editing. **Luca Daniel:** Data Collection, Visualization, Writing - review & editing. **Robert Gaschler:** Conceptualization, Writing – review & editing. **Hilde Haider:** Conceptualization, Writing – review & editing. **Charles H. Shea:** Conceptualization, Methodology, Writing – review & editing.

Declaration of competing interest

The authors have no competing interests to declare.
 The first author declares that he has no conflict of interest.
 The second author declares that she has no conflict of interest.
 The third author declares that he has no conflict of interest.
 The fourth author declares that he has no conflict of interest.
 The fifth author declares that she has no conflict of interest.

Data availability

Data will be made available on request.

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References

- Adams, J. A. (1987). Historical review and appraisal of research on the learning, retention, and transfer of human motor skills. *Psychological Bulletin*, 101(1), 41–74. <https://doi.org/10.1037/0033-2909.101.1.41>
- Bapi, R. S., Doya, K., & Harner, A. M. (2000). Evidence for effector independent and dependent representations and their differential time course of acquisition during motor sequence learning. *Experimental Brain Research*, 132, 149–162.
- Bönstrup, M., Iturrate, I., Thompson, R., Cruciani, G., Censor, N., & Cohen, L. G. (2019). A rapid form of offline consolidation in skill learning. *Current Biology*, 29, 1346–1351. <https://doi.org/10.1016/j.cub.2019.02.049>
- Broeker, L., Kiesel, A., Aufschnaiter, S., Ewolds, H. E., Gaschler, R., Haider, H., et al. (2017). Why prediction matters in multitasking and how predictability can improve it. *Frontiers in Psychology*, 8, 2021. <https://doi.org/10.3389/fpsyg.2017.02021>
- Clegg, B. A., DiGirolamo, G. J., & Keele, S. W. (1998). Sequence learning. *Trends in Cognitive Sciences*, 2(8), 275–281.

- Cohen, J. (1988). *Statistical power analysis for the behavioral sciences* (2nd ed.). Hillsdale, NJ: Erlbaum.
- Conessa, A., Debarnot, U., Siegler, I., & Boutin, A. (2023). Sleep-related motor skill consolidation and generalizability after physical practice, motor imagery, and action observation. *iScience*, 26, 107314. <https://doi.org/10.1016/j.isci.2023.107314>
- Curran, T., & Keele, S. W. (1993). Attentional and non-attentional forms of sequence learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 19, 189–202.
- Elliott, D., Chua, R., Pollock, B. J., & Lyons, J. (1995). Optimizing the use of vision in manual aiming: The role of practice. *Quarterly Journal of Experimental Psychology*, 48, 72–83.
- Faul, F., Erdfelder, E., Lang, A.-G., & Buchner, A. (2007). G*power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, 39, 175–191.
- Frensch, P. A., Buchner, A., & Lin, J. (1994). Implicit learning of unique and ambiguous serial transitions in the presence and absence of a distractor task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 20, 567–584.
- Gaschler, R., Zhao, F., Röttger, E., Panzer, S., & Haider, H. (2019). More than hitting the correct key quickly - spatial variability in touch screen response location under multitasking in the serial reaction time task. *Experimental Psychology*, 66(3), 207–220.
- Haider, H., Eberhardt, K., Esser, S., & Rose, M. (2014). Implicit visual learning: How the task set modulates learning by determining the stimulus-response binding. *Consciousness and Cognition*, 26, 145–161. <https://doi.org/10.1016/j.concog.2014.03.005>
- Hazeltine, E., Ruthruff, E., & Remington, R. W. (2006). The role of input and output modality pairings in dual-task performance: Evidence for content-dependent central interference. *Cognitive Psychology*, 52, 291–345.
- Heuer, H. (1996). Dual-task performance. In O. Neumann, & A. S. Sanders (Eds.), *Handbook of perception and action* (pp. 113–153). San Diego: Academic Press.
- Hikosaka, O., Nakahara, H., Rand, M. K., Sakai, K., Lu, X., Nakamura, K., et al. (1999). Parallel neural networks for learning sequential procedures. *Trends in Neurosciences*, 22(10), 464–471.
- Hommel, B. (2004). Event files: Feature binding in and across perception and action. *Trends in Cognitive Sciences*, 8(11), 494–500.
- Hsiao, A. T., & Reber, A. S. (2001). The dual-task SRT procedure: Fine-tuning the timing. *Psychonic Bulletin Review*, 8(2), 336–342. <https://doi.org/10.3758/bf03196170>
- Keele, S. W., Ivry, R., Mayr, U., Hazeltine, E., & Heuer, H. (2003). The cognitive and neural architecture of sequence representation. *Psychological Review*, 110(2), 316–339.
- Keele, S. W., Jennings, P., Jones, S., Caulton, D., & Cohen, A. (1995). On the modularity of sequence representation. *Journal of Motor Behavior*, 27, 17–30.
- Koch, I., & Hoffmann, J. (2000). The role of stimulus-based and response-based spatial information in sequence learning. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 26, 863–882.
- Kovacs, A. J., Boyle, J., Gruetzmacher, N., & Shea, C. H. (2010). Coding of on-line and pre-planned movement sequences. *Acta Psychologica*, 133, 119–126.
- Kovacs, A. J., Han, D.-W., & Shea, C. H. (2009). The representation of movement sequences is related to task characteristics. *Acta Psychologica*, 132, 54–56.
- Kovacs, A. J., Muehlbauer, T., & Shea, C. H. (2009). The coding and effector transfer of movement sequences. *Journal of Experimental Psychology: Human Perception and Performance*, 35, 390–407.
- Kurata, K., & Hoshi, E. (2002). Movement-related neuronal activity reflecting the transformation of coordinates in the ventral premotor cortex of monkeys. *Journal of Neurophysiology*, 88, 3118–3132.
- Leinen, P., Shea, C. H., & Panzer, S. (2015). The impact of concurrent visual feedback on coding of on-line and pre-planned movement sequences. *Acta Psychologica*, 155, 92–100.
- Marcus, D. J., Karatekin, C., & Markiewicz, S. (2006). Oculomotor evidence of sequence learning on the serial reaction time task. *Memory & Cognition*, 34(2), 420–432. <https://doi.org/10.3758/BF03193419>
- Nissen, M. J., & Bullemer, P. (1987). Attentional requirements of learning: Evidence from performance measures. *Cognitive Psychology*, 19, 1–12.
- Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia*, 9(1), 97–113. [https://doi.org/10.1016/0028-3932\(71\)90067-4](https://doi.org/10.1016/0028-3932(71)90067-4)
- Panzer, S., Krueger, M., Muehlbauer, T., Kovacs, A. J., & Shea, C. H. (2009). Inter-manual transfer and practice: Coding of simple motor sequences. *Acta Psychologica*, 131, 99–109.
- Park, J. H., & Shea, C. H. (2005). Sequence learning: Response structure and effector transfer. *Quarterly Journal of Experimental Psychology*, 58, 387–419.
- Pfeifer, C., Panzer, S., & Shea, C. H. (2022). Attentional demand of a movement sequence guided by visual-spatial and by motor representations. *Journal of Motor Behaviour*. <https://doi.org/10.1080/00222895.2022.2101424>
- Röttger, E., Haider, H., Zhao, F., & Gaschler, R. (2019). Implicit sequence learning despite multitasking: The role of across-task binding predictability. *Psychological Research Psychologische Forschung*. <https://doi.org/10.1007/s00426-017-0920-4>
- Röttger, E., Zhao, F., Gaschler, R., & Haider, H. (2021). Why does dual-tasking hamper implicit sequence learning? *Journal of Cognition*, 4(1), 1. <https://doi.org/10.5334/joc.136>
- Sakai, K., Hikosaka, O., Miyauchi, S., Takino, R., Sakaki, Y., & Putz, B. (1998). Transition of brain activation from frontal to parietal areas in visuo-motor sequence learning. *Journal of Neuroscience*, 18, 1827–1840.
- Schmidtke, V., & Heuer, H. (1997). Task integration as a factor in secondary-task effects on sequence learning. *Psychological Research*, 60(1–2), 53–71. <https://doi.org/10.1007/BF00419680>
- Schumacher, E. H., & Schwarb, H. (2009). Parallel response selection disrupts sequence learning under dual-task conditions. *Journal of Experimental Psychology: General*, 138(2), 270. <https://doi.org/10.1037/a0015378>
- Shea, C. H., Kovacs, A. J., & Panzer, S. (2011). The coding and inter-manual transfer of movement sequences. *Frontiers in Psychology*, 2, 52. <https://doi.org/10.3389/fpsyg.2011.00052>
- Shin, J. C., & Ivry, R. B. (2002). Concurrent learning of temporal and spatial sequences. *J Journal of Experimental Psychology: Learning, Memory, and Cognition*, 28(3), 445–457. <https://doi.org/10.1037/0278-7393.28.3.445>
- Smiley-Oyen, A. L., & Worringham, C. J. (2001). Peripheral constraint versus on-line programming in rapid aimed sequential movements. *Acta Psychologica*, 108, 219–245.
- Verwey, W. B., & Clegg, B. A. (2005). Effector dependent sequence learning in the serial RT task. *Psychological Research*, 69, 242–251. <https://doi.org/10.1007/s00426-004-0181-x>
- Waszak, F. (2010). Across-task long-term priming: Interaction of task readiness and automatic retrieval. *The Quarterly Journal of Experimental Psychology*, 63, 1414–1429.
- Winer, B. J. (1971). *Statistical principles in experimental design*. New York: McGraw-Hill.