Effects of frame of reference on the spatial and motor component in the early and late learning stages of procedural learning

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Enschede, August 19, 2009

Abstract

Research has shown that procedural learning of sequences can be split into an early and a late stage of learning. It is further assumed that spatial and motor systems are not equally active during these stages. The spatial system is assumed to be primarily active during the early learning stage, whereas the motor system is assumed to be most active during the late learning stage. This research study tests if these two systems differ in their activity during the early and late learning stage. For this purpose, the participants performed a Discrete Sequence Production (DSP) task. After a practice phase they were forced to change their hand and eye-centered frame of reference in either the early or late learning stage. The results show that the motor system is indeed heavily active during the late learning stage. The spatial system however was not found to be dominantly active in only one stage. These results indicate that the spatial system is active in the early learning stage as well as in the late learning stage.

Keywords: sequence learning, finger frame of reference, change in frame of reference, motor system, visual-spatial component

Introduction

Every action we perform can be broken down into simple movements (de Kleine & Verwey, 2009). To perform a complex movement, these simple movements have to be combined so that a sequence develops. These movements do not appear from nowhere; they are accomplished through learning. To learn a motor skill, a person has to learn the simple movements for this motor skill one by one (Liu, Lungu, Waechter, Willingham, & Ashe, 2007). In other words, the accomplishment of voluntary behavior is reached by learning the sequential procedures of this behavior (Willingham, Nissen, & Bullemer, 1989).

The learning of a new action or skill is called procedural learning and the knowledge of the movement pattern is stored in procedural memory. The actual learning takes place during physical practice. Improvement of the new skill is accomplished through practice and attention (Vidoni, & Boyd, 2007). At the beginning of learning a new skill, it is initially necessary to pay careful attention to the task. However with practice the skill becomes more automatic until no attention is needed. When a stage of automaticity is reached, attention can even be directed to another task (de Kleine & Verwey, 2009). For example, the first time somebody uses a computer keyboard, the person has to search for every key until he has memorized the arrangement of the keys and is able to type without paying attention to where the keys are located. It seems as if the fingers know where to find the keys and how to perform the movements, enabling the person to direct his attention to another task (Bapi, Doya, & Harner, 2000).

Generally, the learning of a sequence can be divided into two learning stages, the early and the late learning stage (Hikosaka, Sakai, Lu, Nakahara, Rand, Nakamura, Miyachi, & Doya, 1999). The differences between these two stages lies in how the sequences are executed and memorized. In the early learning stage the sequence is quickly established, but also lost rapidly if it is not practiced further. Because of this characteristic it is assumed that the practiced sequence is memorized in short-term memory during the early learning stage. Moreover, in the early learning stage more attention is needed to correctly fulfill the movement. On the other hand to achieve the late learning stage, much practice is needed. Thus, it takes time to reach the late learning stage. If this is accomplished the sequence will be remembered longer. Therefore it is assumed that the sequence is stored in long-term memory when the late learning stage is reached. Additionally, less attention is needed for executing the sequence during the late learning stage (Hikosaka et al., 1999).

Frame of reference

Objects are often used for executing a particular movement, such as in the example of typing, where a computer keyboard is used. Therefore, it is important to know how an object in space is perceived. For this purpose a frame of reference is used. There are two types of frames of reference, allocentric and egocentric ones. The former uses an external reference point to localize an object in space. An example could be the observation: “the keyboard is next to the table”. In an egocentric frame of reference the object is localized in space in reference to one’s own body. For example: “the keyboard is in front of me” (Witt, Ashe, & Willingham, 2008). It was shown that people learn movement sequences in an egocentric frame of reference (Liu et al., 2007). However, there are multiple egocentric frames of reference which can be used to execute a movement, such as a body-centered or hand-centered frame of reference. For example, when using the hand as a frame of reference, the movement would be performed in relation to the hand. In this case, only the executing hand, the effector, can use this hand-centered frame of reference. In other words, such a hand-centered frame of reference is effector-dependent. It was found that a hand-centered frame of reference is used for reaching movements (Witt et al., 2008). Thus, if somebody wants to reach for an object and has to correct the movement, this correction will be related to the position of the hand. However as noted earlier, a larger body part can also be used as a frame of reference, such as a trunk-centered frame of reference. Here, the movement is related to the whole trunk. Such a frame of reference is usable by several body parts and is not only restricted to the effector. Therefore it is said that this frame of reference is effector-independent (Witt et al., 2008).

It can be assumed that the effector-specific and body-centered frames of reference are associated with the early and late learning stages. Specifically, it is expected that a body-centered frame of reference is used during the early learning stage. This indicates that more effectors can use this frame of reference. Therefore the early learning stage is effector-independent. However, when automaticity is achieved in the late learning stage, the execution of the sequence is effector-dependent, because an effector-specific frame of reference is used. (Witt et al., 2008). Thus in the late learning stage, only the body part which learned the sequence is able to execute the action without error or decline in speed (Rand, Hikosaka, Miyachi, Lu & Miyashita, 1998). Therefore, it is concluded that there is a transfer from using a body-centered frame of reference to an effector-specific frame of reference (Witt et al., 2008).

Spatial and motor component

For a long time it was believed that learning and execution of a movement could only take place in a serial manner (Allen & Tsukahara, 1974, cited in Hikosaka et al., 1999). However, Hikosaka et al. (1999) developed a model which they claim better fits the learning process of a sequence. They distinguish between three different stages in which two different systems are active, the spatial and the motor system. These two systems are unequally active during the early and late learning stages (de Kleine & Verwey, 2009).

Hikosaka et al. (1999) assumed that in the pre-learning stage the serial sensorimotor process plays an important role. In other words, the sensory input is transferred to a motor output in a serial manner. That is, a person receives a sensory stimulus and transfers this stimulus into motor output, e.g. response movement. Thus the spatial and motor systems are passed through in a serial manner. First the spatial system is active and then the motor system. By naming it the pre-learning stage it is indicated that learning has not taken place yet. It is just a simple stimulus response execution without memorizing the movement (Hikosaska, 1999).

New in their model is that the spatial and motor systems work in parallel when the sequence is repeated. This means that the execution of a sequence no longer relies on the serial sensorimotor process. In the early learning stage the spatial system dominates, whereas ultimately the motor system is dominant in the late learning stage. This indicates that sequence execution relies heavily on spatial components in the early learning stage and on motor components in the late learning stage. As mentioned earlier the late learning stage is effector-dependent, therefore only the effector which practiced the sequence uses the motor information. During the early learning stage a body-centered frame of reference is used and several effectors can use the spatial information which is provided by this frame of reference (Hikosaka, 1999).

Chunking

Research has shown that sequences are learned by using motor chunks (Sakai, Kitaguchi, & Hikosaka, 2003). The original definition of a chunk was developed by Miller (1956, cited in Sakai et al., 2003) and was used to explain how series of information can be memorized. During chunking several memory symbols, such as multiple digits of a telephone number, are taken together as one whole. This memory chunk consists of several facts (e.g.

digits) but is stored as one memory representation (Miller, 1956, cited in Sakai et al., 2003). Later it was found that motor sequences are also memorized by breaking down a large sequence into smaller subsequences. Thereby creating memory chunks for motor movements (Sakai et al., 2003). These subsequences are called motor chunks. The usage of a motor chunk is the same as the usage of a memory chunk for facts. The only difference is that motor chunks represent movements. Learning a skill depends on developing motor chunks, because these have to be combined to execute a movement. The motor chunks are favorable for the capacity of the working memory, because they help to overcome the limits of the working memory. It is more efficient to group individual memory symbols for a sequence together as one symbol than to memorize every single symbol (Sakai et al., 2003). However, there is a limit to how many symbols can be coded into one motor chunk. Verwey, Lammens and van Honk (2002) have found that the limit is usually reached at three elements for one motor chunk, but the number of elements that fits in one chunk can differ per individual. Often a sequence is executed rhythmically, in which case the rhythm is coupled to the motor chunk. Once a rhythm is established it is inseparable from the sequence (Sakai, Hikosaka, & Nakamura, 2004). A rhythm can even influence how a sequence is split into several motor chunks. If a sequence was practiced with a pause this imposes the development of a new chunk (Verwey, 1996).

Hypotheses

Many studies have been done on sequences in procedural learning, but much remains unclear. The following experiment aims to provide more information on sequence learning and to test and extend the assumptions of the model developed by Hikosaka et al. (1999). In the present study a discrete sequence production (DSP) task is executed. During a DSP task the participants learn sequences on a computer keyboard and have to press keys with assigned fingers. The reaction time (RT) and accuracy is measured.

This experiment is a 2 (group: low practice vs. high practice) x 2 (fingers: familiar vs. unfamiliar) x 2 (fixation cross: new vs. old) x 2 (pause in practice: pre-structured vs. unstructured) x 6 (keys: the sequence) design. The participants were divided into 2 groups: one with a short practice phase (low practice), the other one with a long practice phase (high practice). Both groups had a practice phase which only differed in duration. In this phase they practiced 2 sequences, which consisted of 6 key combinations, with assigned fingers. During the execution they were focusing on a particular fixation cross on the display. One of the sequences was presented with a built-in pause (pre-structured) and one without (unstructured). In the test phase, both learned sequences were presented as an unstructured sequence. The variables finger and fixation cross were also changed in the test phase. This means that the participants had to perform the sequences with either the same fingers as in the practice phase or with other fingers. The same was applied for the fixation cross. Thus the participants had to either focus on the same cross in space or on a different fixation cross. These two variables were counterbalanced.

The experiment aims to demonstrate which frame of reference is used in the early and late learning stage and how this interacts with chunking. It is assumed that when the participants use an effector-specific frame of reference the change in fingers would impair the execution of the sequence. The fingers rely on the motor component of the sequence and thus a change in fingers is not possible. This would be most likely in the late learning stage. However, when the participants use an eye-centered frame of reference, execution of the sequence worsens when the position of the fixation cross changes. By using an eye-centered frame of reference, execution relies on the visual-spatial component of the sequence. By changing the fixation cross this interferes with the visual-spatial information. It is expected that this visual-spatial information is used during the early learning stage. In general, it is assumed that there will be an increase in reaction time and error when the frame of reference (on which the spatial or motor component relies) is changed. For that reason the participants were forced to change their frames of references.

As a result, the first hypothesis for this experiment is that in the early learning stage the participant can easily change the fingers for the execution of the DSP task. The early learning stage is effector-independent and the spatial component is active. Therefore a body-based frame of reference is used, namely an eye-centered frame of reference. In other words, the first hypothesis is that for the low practice group there is no change in response time and in error rate if the participants use other fingers in the test phase than in the practice phase. The second hypothesis is that for the low practice group there is an increase in reaction time (RT) and error rate if the participants have to focus on another point in space in the test phase, because the spatial component relies on the visual-spatial information from the eye-centered frame of reference. The hypotheses for the late learning stage are exactly the other way around. It is assumed that in this stage a hand-centered frame of reference is used, because the motor component is highly active. In this case a effector-specific frame of reference is used. Thus, for the high practice group the mean RT and error rate stays the same if the participants have to focus on another point in space in the test phase. On the other hand, for the high practice group the mean RT and error rate are expected to increase when the participants have to use different fingers in the test phase.

Method

Participants

Twenty-eight (18 female and 10 male) students from the University of Twente participated in the present study. Their ages ranged from 19 to 29. All participants received course credits for participation. The participants were divided into two groups, a low practice and high practice group. For the actual analysis only 24 participants were used, to provide a balanced experiment across the 6 possible sequences and 2 different groups (low vs. high practice). As a result, four participants had to be excluded from the analysis. If in one group (low or high practice) were 2 participants who executed the same sequences with the same instructions, one had to be eliminated from the analysis. The exclusion was based on the accuracy at recording the control variable (intended to check if the participant followed the instructions). This control variable is explained in more detail further on.

Apparatus

For the present study two Pentium IV PCs were used. The computers were located in two different rooms. It is assumed that the room had no effect on the results, because the participants were divided equally over both rooms. So if there was a room effect this is balanced over the two groups. E-prime 2.0 was used on Windows XP for the representation of the stimulus, with as few as possible background processes running. This made an accurate measurement of the reaction time possible. The participants used a standard QWERTY keyboard to act on the stimulus. A chinrest was used which was placed at 50cm in front of the computer screen to assure a constant viewing position for all participants. The computer screen’s refresh rate was 75 Hz.

Task

The participants completed a discrete sequence production (DSP) task with their index and middle fingers of both hands. These fingers have been chosen, because no differences have been found in their ability to perform or in their reaction speed (Aoki, Francis & Kinoshita, 2003). The other fingers do differ in these variables, because of differences in the extensor muscles and amount of practice (Aoki, & Kinoshita, 2001). Therefore, the participants used either the index finger of the left hand and the index finger and middle finger of the right hand or the middle finger and index finger of the left hand and the index finger of the right hand.

The participants sat in front of a computer screen on which three squares were shown. These squares were 2 by 2 cm in size and the space between them was 5 cm. The squares appeared on a white background. In the practice phase a gray X was shown 7 cm to the right of the squares. The participants laid their chin on the chinrest and were instructed to focus on the X, the fixation cross. The shown squares were coupled with specific keys. The left square corresponded with the ‘F’ key, the middle one with the ‘G’ key and the right square corresponded with the ‘H’ key. During the experiment the squares filled with the color green, which was the stimulus to press the corresponding key. For example if the left square filled green, the participants had to press the ‘F’ key. To press the ‘F’ key the participants had to use their leftmost finger (either middle or index finger of the left hand), the following finger had to press the ‘G’ key and the rightmost finger had to press the ‘H’ key, see also table 1. During this task they had to keep their gaze on the fixation cross. Thus, the participants saw the stimulus only in their peripheral visual field.

To make sure that the participants did focus on the fixation cross, the fixation cross randomly lit up in red. The participants had to count how many times they saw the color of the X change. In the middle and end of a block they had to type how many times they saw a red X. Immediately after typing the number of red Xs, the system showed how many red Xs there actually had been in the last block, how many mistakes they had made and what their mean reaction time had been. If the participants pressed a wrong key an error message was provided and the participant had to correct the mistake. The same happened if the participant pressed too early or too late, after which the participant had to correct by pressing the proper key. An early or late respond was counted as a mistake, too. In this way the participants learned two specific sequences which consisted of six key presses.

Table 1 Setup of the experiment

Subject low practice group	Subject high practice group	Unstructured sequence	Pre-structured sequence	Fingers in Practice Phase	Fixation Point in Practice Phase	Fingers in Test Phase, unfamiliar	Fixation Point in Test Phase, new
1	13	FHGHFG	HFGFHG	L-mi, L-in, R-in	Right	L-in, R-in, R-mi	Left
2	14	HGHFGF	FGFHGH	L-in, R-in, R-mi	Right	L-mi, L-in, R-in	Left
3	15	GHFGFH	GFHGHF	L-mi, L-in, R-in	Right	L-in, R-in, R-mi	Left
4	16	HFGFHG	FHGHFG	L-in, R-in, R-mi	Right	L-mi, L-in, R-in	Left
5	17	FGFHGH	HGHFGF	L-mi, L-in, R-in	Right	L-in, R-in, R-mi	Left
6	18	GFHGHF	GHFGFH	L-in, R-in, R-mi	Right	L-mi, L-in, R-in	Left
7	19	FHGHFG	HFGFHG	L-mi, L-in, R-in	Right	L-in, R-in, R-mi	Left
8	20	HGHFGF	FGFHGH	L-in, R-in, R-mi	Right	L-mi, L-in, R-in	Left
9	21	GHFGFH	GFHGHF	L-mi, L-in, R-in	Right	L-in, R-in, R-mi	Left
10	22	HFGFHG	FHGHFG	L-in, R-in, R-mi	Right	L-mi, L-in, R-in	Left
11	23	FGFHGH	HGHFGF	L-mi, L-in, R-in	Right	L-in, R-in, R-mi	Left
12	24	GFHGHF	GHFGFH	L-in, R-in, R-mi	Right	L-mi, L-in, R-in	Left

L-mi: Left middle finger, *L-in:* Left index finger, *R-in:* Right index finger, *R-mi:* Right middle finger
Test phase also included the variable finger: familiar (as in practice phase)

Six key orders were possible which resulted in six different sequences. However, the total number of alternative sequences was 12, because every sequence could be represented with or without a non-aging interval. When using a non-aging interval the sequence is represented with a pause between the third and fourth key press, this sequence is called pre-structured. It is known that the participant splits the sequence into two motor chunks at the non-aging interval. Without a non-aging interval (unstructured sequence) there is no certainty about how the subject splits the sequence into motor chunks (Verwey, 1996). If effects are found then it would be possible with the aid of a pre-structured sequence in which phase of the sequence the effect is found, because then it is exactly known where one motor chunk ends and the other begins. To prevent that a rhythm was learned, the non-aging interval could vary between 300 and 2000ms. The duration of the pause depended on randomization with a larger chance of a short pause.

Procedure

The participants had individually chosen to sign up for the long or short version of the experiment. Before participating in this study the participants signed a confirmed consent. Every participant learned two sequences, one pre-structured and one unstructured. At the beginning of the practice phase they were told which fingers to use for pressing a key.

For each sequence there were 50 trials in each practice block. Because every participant practiced two sequences, there were a total of 100 trials in each block. In the middle of a block they had a 20 second break and at the end of a block they had a 3 minute break. The difference between the low and high practice group was the number of practice blocks. The low practice group had one practice block, thus practicing each sequence 50 times. The high practice group had 9 practice blocks and thus practiced each sequence 450 times.

The test phase was the same for both groups and all sequences were presented as an unstructured sequence. The key order of the sequences stayed the same; only the non-aging interval was removed. In the test phase the instruction for the execution of the sequences varied. In total there were four counterbalanced sub blocks. The two independent variables changed: fingers (familiar vs. unfamiliar) and fixation cross (new position vs. old position), see table 1. For the variable ‘fingers’ it meant that the participants used other fingers than in the practice phase. For instance, if they used the index finger of the left hand and the index and middle finger of the right hand in the practice phase, they now used the middle and index finger of the left hand and the index finger of the right hand during the test phase. Therefore the instruction each participant received depended on the practice phase they had had. For the variable ‘fixation cross’ it meant that the fixation cross was placed to the left of the squares instead of to the right.

Each ‘finger’ variable was counterbalanced with each ‘fixation cross’ variable, so that four sub blocks were created. The order of the sub blocks was counterbalanced across the participants, to exclude an order effect. Each sub block consisted of 25 trials per sequence, therefore 200 trials were completed in the test phase by each participant.

Data analysis

For an adequate reaction time (RT) analysis, all sequences in which one or more mistakes had been made were excluded. This was about 2 percent per key across all participants and blocks. Moreover, the sequences with a too long RT are excluded. To assure that not too much data was ignored, a limit for the mean response time was chosen at 700ms. This corresponds to the mean response time for all participants plus 2.8 standard deviations. In this way 2 percent of the data has been excluded from analysis. The performance on the counting task, counting the red Xs, was not deeply analyzed, it was only used to see if the participants followed the instructions. For a few subjects there were only one or two outliers in reporting the correct red Xs. Especially in the test phase the participants counted the number or red Xs very accurately. In only 4 percent of the cases a miscount of 7 or greater was recorded. The number of the shown red Xs was between 10 and 56. Therefore, it is clear that the participants had actually focused at the fixation cross and thus followed the instructions.

The program only registered in which sequences errors had been made, it did not save at which key the mistake had been made. Therefore, it was not possible to analyze the error rate for specific keys.

An analysis of variance (ANOVA) with repeated measures has been used for the analysis of the reaction time of every key and the (arcsine transformed) error rates. For the analysis of reaction time, the within subject factors were: fingers (unfamiliar vs. familiar), fixation cross (old vs. new), pause in practice (pre-structured vs. unstructured) and key (sequence). The between subject factor was amount of practice (low practice group vs. high practice group). For the error rate the same within and between subject factors were used except the variable key, because this was not recorded.

Results

Because participants were allowed to choose between the low and high practice group, a check was done to see if group composition had a significant effect on response time during the first session. A t-test showed that the two groups did not differ significantly in their reaction time in the first session ($t(0.95,14419)= 0.59, p < 0.557$). Thus, it is safe to say that effects found in the analysis cannot be attributed to the composition of the groups.

For the practice phase it can be said that the participants became faster over time ($F(8,4) = 18.09, P < 0.007$). This showed that the participants did learn the sequences. This

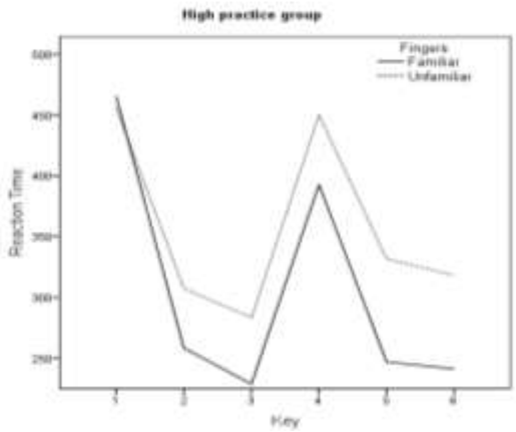

Figure 1: RT for fingers and key, high practice group

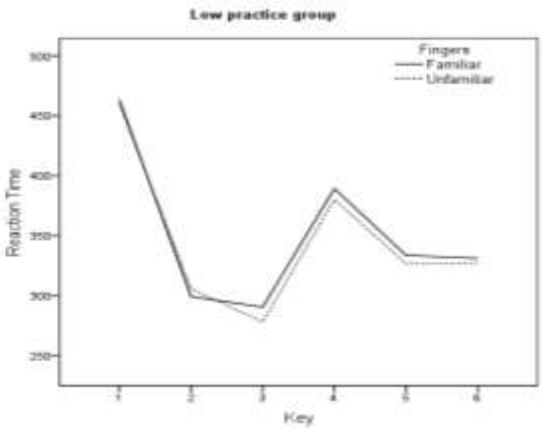

Figure 2: RT for fingers and key, low practice group

was the basis for the subsequent analysis of the test phase.

First, all significant effects for the variable fingers will be presented, see also figure 1 and 2. In the test phase a main effect of fingers was found ($F(1,22) = 5.85$, $P < 0.024$). A pairwise comparison test showed that the sequences were executed faster with the familiar fingers (the ones used in the practice phase) than with the unfamiliar fingers. The same pattern was also confirmed with a post hoc analyses for the mistakes the participants had made. More mistakes were made with the unfamiliar fingers than with the familiar fingers ($F(1,22) = 4.38$, $P < 0.048$). Further analysis showed that there is an interaction effect between the group and finger variables ($F(1,22) = 7.57$, $P < 0.012$). A post hoc analysis indicated that the high practice group needed more time to execute the sequences with the unfamiliar fingers than the low practice group. Moreover, the high practice group became faster with practice in executing the sequence with the familiar fingers. Thus, the high practice group had a bigger difference in reaction time between the unfamiliar and familiar fingers. This provides evidence that the sequences were coupled to the effector in the late learning stage, but not in the early learning stage. Moreover, an interaction effect between fingers and pause in practice was found ($F(1,22) = 8.2$, $P < 0.009$). A post hoc analysis showed that the participants made a greater distinction between the two sequences when they executed the sequences with the familiar fingers. Thus, the pre-structured sequence only had an effect on the execution when the participants performed the sequences with the familiar fingers.

For the error rate, a significant interaction effect was also found for fingers and pause in practice ($F(1,22) = 4.69$, $P < 0.041$). The post hoc analysis showed that there is only an effect of pre-structured sequence when the sequences were executed with the familiar fingers. Less mistakes were made when the unstructured sequences were executed with the familiar fingers.

Summarizing for the variable finger, participants from the high practice group (with familiar fingers) were both faster and more accurate when executing the unstructured sequence than when executing the pre-structured sequence. As a conclusion for the variable finger, the most important result is that the high practice group coupled the sequence to the effector. This had an impact on the reaction time when the hand-centered frame of reference changed, indicating that the fingers relied on the motor component.

For the variable fixation cross not many significant effects were found, see figure 3 and 4. Only a main effect of fixation point on RT was found ($F(1,22) = 5.69$, $P < 0.026$). Pair-wise comparison showed that the RT increased when the fixation point changed from the old to the new position. However, no difference was found between the two groups (low vs. high practice group).

A main effect was found for the variable pause in practice ($F(1,22) = 4.57$, $P < 0.044$). Pair-wise comparison showed that the unstructured sequences were executed faster than the pre-structured sequences. Thus, the non-aging interval was part of the sequence, even when the sequence was presented without a non aging interval in the test phase. That indeed the sequence was executed with a non-aging interval between key three and four is supported by the interaction effect between key and pause in practice ($F(5,18) = 5.84$, $P < 0.002$). A post

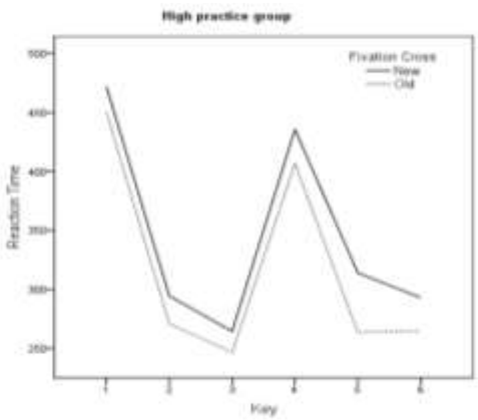

Figure 3: RT for fixation cross and key, high practice group

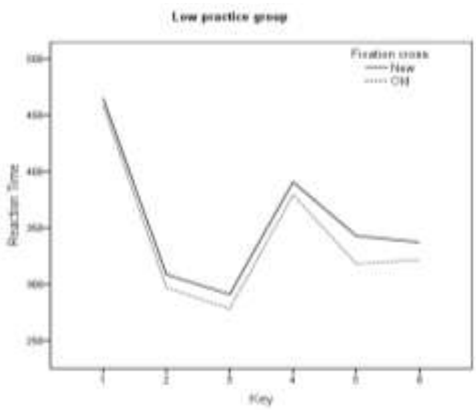

Figure 4: RT for fixation cross and key, low practice group

hoc analysis provided evidence that the pre-structured sequence was executed slower at the first and fourth key. However, the slowing of key 4 was also found in the unstructured sequence. It seems as if the non-aging interval was carried over to the unstructured sequence.

The pre-structured sequence was more established in one of the two groups ($F(1,22) = 7.42$, $P < 0.012$). With a post hoc analysis the greatest effect was found for the high practice group. The participants in the high practice group made a greater distinction between the pre-structured and unstructured sequences. The non-aging interval could also be the cause why some keys are executed faster than others ($F(5,18) = 22.32$, $P < 0.000$). A post hoc analysis showed that the first and fourth key, before which the interval was placed, were executed slower. Another post hoc analysis showed that this effect was significantly more present in the high practice group ($F(5,18) = 3.74$, $P < 0.017$).

To summarize, the participants learned the two sequences. For the high practice group the learned sequence was coupled to the fingers, but this was not the case for the low practice group. They could still change their fingers without an increase in reaction time and error rate. For the fixation cross it was found that the reaction time increased for both groups when the fixation cross was placed at a new position. It was also shown that when practicing a sequence with a non-aging interval, this interval becomes inseparable from the sequence, even when the non-aging interval is removed, especially for the high practice group.

Discussion

This study was designed to test whether different frames of references are used in the early and late learning stage and what the effects of these frames of references are on the spatial and motor component. Moreover, it was tested if the frames of references interacted with chunking.

In general, it can be said that the participants learned the sequence, because over time they became faster in the execution of the sequences. The main aim of this study was to test Hikosaka et al.'s (1999) model and to find effects of the frame of reference on the spatial and motor component. It was hypothesized that for the low practice group it did not matter which fingers they used to execute the sequences. This is proven with this experiment. No increase in reaction time was found when the participants changed their fingers in the early learning stage. This shows that the sequence is not coupled to the effector yet: it is effector-independent. This also proves that changing the effector-specific frame of reference in the early learning stage has no effect on the knowledge provided by the motor component.

The second hypothesis predicted that in the early learning stage the reaction time would increase when the fixation cross position changed. This was indeed the case: an increase in reaction time was found when the eye-centered frame of reference (fixation cross) changed. This shows that the visual-spatial information gets influenced through a change in eye-centered frame of reference. For the early learning stage it can be concluded that the spatial system is heavily active. Moreover, the spatial component relies on information received through an eye-centered frame of reference. Therefore, the early learning stage is effector-independent. If the eye-centered frame of reference changes, this has an impact on the execution of the learned action. The reason could be that the sequence is practiced in relation to the eyes. Thus if this relation changes it is not possible to execute the sequence without an increase in reaction time, because this stage relies on the visual-spatial information. Another explanation could be that the participants learned the sequence through peripheral perception and that this is a specific skill. Thus the participants only learned to see the stimuli on their left periphery and that this such a specific skill that it is not possible to transmit this skill to see stimuli on the right periphery.

For the late learning stage it was predicted that the participants would not be able to perform the sequence with the unfamiliar fingers without an increase in reaction time. In this study it was found that there was indeed an increase in reaction time when the participants changed their fingers in the late learning stage. This supports the hypothesis that a hand-centered frame of reference is used in the late learning stage. Moreover, this is also evidence that the motor component gets influenced by the effector-specific frame of reference. If this was not the case,there would be no increase in reaction time reported. This is in line with Hikoska et al.’s (1999) model and these findings also explain why the late learning stage is effector-dependent. It could even be that the frame of reference is so specific that it is coupled to the individual fingers and therefore it is not possible to use other fingers for the same action. Note that the frame of reference is even so specific that only the specific fingers used this frame of reference and not the whole hand, otherwise the participants would be able to change their fingers of the same hand.

For the late learning stage it was also hypothesized that the reaction time stays the same when the fixation cross, the eye-centered frame of reference, changes. However, this was not found. It was found that also for the participants in the late learning stage the reaction time increased when the fixation point changed. This is rather surprising, because it was assumed by Hikosaka et al.’s (1999) model that in the late learning stage the motor component is heavily active. If this is true, the participants would be able to change their global frame of reference, because the spatial component (which relies on the eye-centered frame of reference) is hardly active. The results of the experiment indicate that the spatial component is also active in the late learning stage. It seems as if Hikosaka et al.’s (1999) model underestimates the spatial component in the late learning stage. They did not deny that the spatial component is active, but they thought that the motor component is more dominant (Hikosaka, 1999). This cannot be verified with this study, but the results do indicate that the spatial component is more active in the late learning stage than initially expected. Thus in the present study no evidence has been found that there was a complete transfer from the eye-centered frame of reference to the hand-centered frame of reference. It would be recommended to study this in another experiment. It could have been that an eye-centered frame of reference was already too specific. Maybe a more global frame of reference would be more appropriate, such as an upper-body frame of reference. In that case, the spatial component might only be found to be active in the early learning stage.

The results show that the participants had divided the sequences with a non-aging interval in two motor chunks, even when the interval was removed. This finding is in line with previous reports by Verwey (1996). In that research, it was found that people hold on to their practiced sequence and chunking, even when the chunking was not the most favorable for their memory (Verwey, 1996). Therefore, the results that the participants had an increase in reaction time at the fourth key are in agreement with the earlier findings: the earlier chunking became inseparable from the sequence. It was more surprising that there was also an increase in reaction time between the third and fourth key for the unstructured sequences. Earlier, it was found that the non-aging interval is not transferred to a sequence without a non-aging interval when one sequence was practiced with a non-aging interval (Verwey, Abrahamse, & Jiménez, 2009). Therefore, the findings of the current experiment are in conflict with the findings of Verwey et al. (2009). A possible explanation is that the sequences without a non-aging interval had a replicate of a chunk which also occurred in the sequences with a non-aging interval, see table 1. For example, when a participant had the key order HGHFGF as the sequence without a non-aging interval, then the participant had the key order FGFHGH as the sequence with a non-aging interval. The last sequence is the same as the first only that the three key chunks are turned around. Maybe the participants coupled this particular chunk to a non-aging interval for both sequences. Moreover, sometimes the unstructured sequence was the reversal of the pre-structured sequence and maybe the participants also reversed the non-aging interval for the unstructured sequence.

It must be noted that not all variables were controlled in this study. It has not been checked if there is a difference if several participants practice with their fixation cross left to the stimuli and other with the fixation point on the right of the stimuli. Additionally, it is questionable if counting the red Xs is sufficient to check if the subjects focused on the fixation point. It could have been that the participants focused on the squares and saw the X in the peripheral visual field. It would be recommended to record the eye movement to be certain on what the participants focused. Another advantage of eye recording would be that the double task of counting and executing a sequence would be excluded. This would ensure that the double task would have no effect on the results.

The point at which the transition between early and late stages of learning takes place is not expected to be fixed and equal for each participant. Most likely this is a gradual transition. In the literature, no indications have been reported on when the transition from early to late stage is most likely to take place. However, there will most likely be a range in which the majority of the subjects has reached the late learning stage. For this research it is assumed that the majority of the high practice group subjects have reached the late learning stage.

As a conclusion, it is shown that with practice a sequence is coupled to the effector and that execution with the practiced effector is faster than with an unpracticed effector. The motor component is developed and plays an important role in the late learning stage, in line with the model proposed by Hikosaka et al. (1999). However, it seems that the role of the spatial component was underestimated by this model and that the spatial component is important for the early learning stage as well as for the late learning stage. To reach a firmer conclusion on the role of the spatial component, more research is needed in this area.

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