Inge S. ter Schegget Acquiring sequential motor skill: What's the next move?

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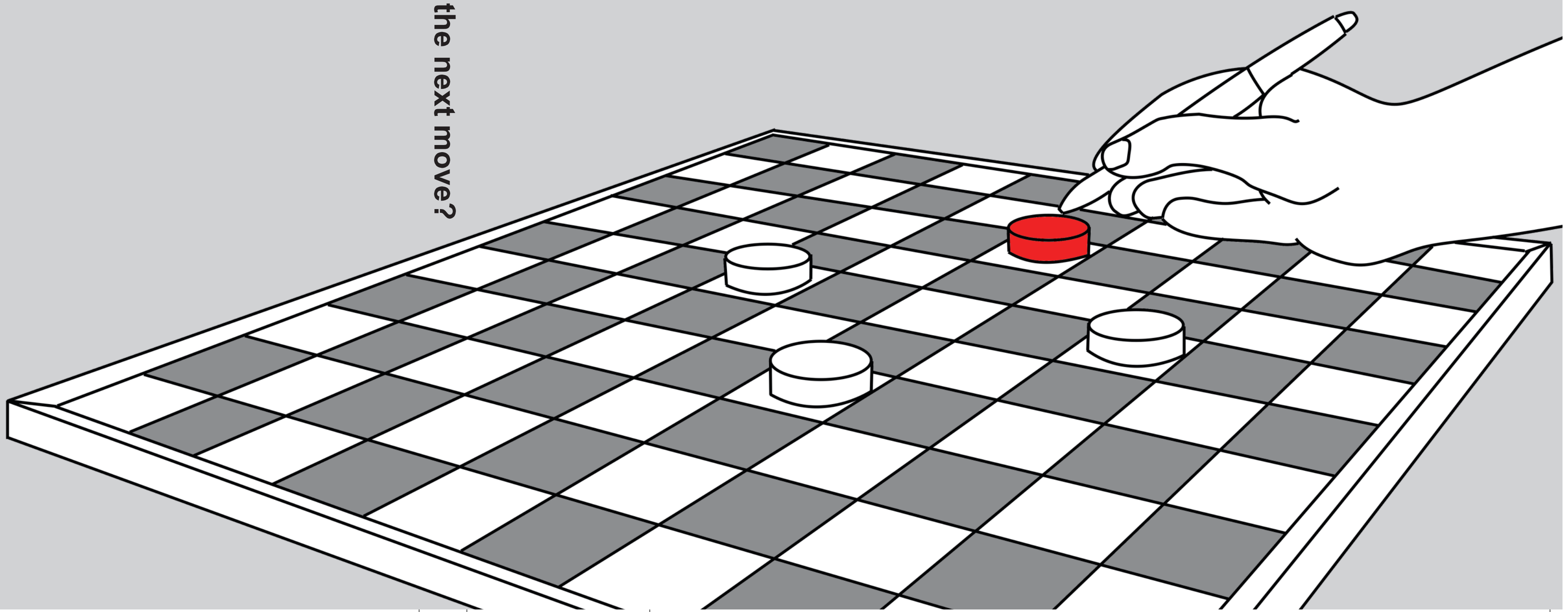

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Acquiring sequential motor skill: What's the next move?

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Acquiring sequential motor skill: What's the next move?

Inge S. ter Schegget

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ACQUIRING SEQUENTIAL MOTOR SKILL: WHAT'S THE NEXT MOVE?

PROEFSCHRIFT

ter verkrijging van
de graad van doctor aan de Universiteit Twente,
op gezag van de rector magnificus,
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volgens besluit van het College voor Promoties
in het openbaar te verdedigen
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door

Inge Simone ter Schegget
geboren op 23 september 1971
te Stad Delden

Dit proefschrift is goedgekeurd door de promotor
prof. dr. ing. W.B. Verwey

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Preface

Early in life I discovered the pleasure of playing with other kids, although I also enjoyed playing alone. Perhaps this is why I always loved playing tennis: in the singles I had to rely on myself, and in the ladies or mixed doubles I had a partner I could count on. My PhD research, with as a result this dissertation, was like playing an exciting tennis match in the finals at Wimbledon.

I owe thanks to a number of people who provided their support in different ways. First I want to thank my opponent and "Doktorvater" Willem Verwey. Willem, thank you for your support in content, enthousiasm and constructive criticism. The umpire Herbert Heuer, thank you for providing the equipment I used for my exeriments. The linesmen, Bianca Groen, Alvine Gross, Peter Kemper, Nadine Nierhaus, Christiaan Rombouts, Ralf Speek, Maxie Strate, Christ Wanrooij and Jacob Wiebenga, thank you for providing support with the participants. The public and colleagues from the departments CPE and OSC: thank you for supporting me by listening to me and discussing with me.

The ballboys and ballgirls, my friends, thank you for keeping my spirit high by helping me in all possible ways. The peptalks, conversations and all kinds of social things gave me the energy to continue. I did not have the time to visit all new homes and babies. Hopefully I will have more time for socialising in the near future. The coaches, my parents, thank you for being there. Whenever I need you, you are there for me. Finally, and most importantly, I want to thank my mixed partner Martijn. Martijn, there are no words to describe your help and support with this dissertation. We played five tie-breaks, but we won. You deserve a big dutch king.

Deventer, 8 april 2009
Inge

Chapter 1

General introduction

1.1 Aim

Human beings constantly show sequential motor behavior in their everyday life. This is clearly demonstrated in activities like typing and playing the piano: When playing a piece of music, all notes must be played in a certain order; otherwise one will hear a totally different melody. However, sequential motor behavior also involves more everyday actions like putting your shoes on before tying the laces, or opening a door before entering a room. Often, the sequential knowledge that underlies this behavior is implicit; that is, people are not consciously aware of the details of their actions.

The aim of the present dissertation is to unravel mechanisms underlying implicit and explicit sequence learning when the sequence is built on aiming movements. The serial reaction time (RT) task developed by Nissen and Bullemer (1987) is used because it is especially suitable for assessing implicit learning. In the typical serial RT task, participants respond to a series of signals by pressing the corresponding response keys. What they usually do not know, is that the signals are presented in a certain order. Participants appear to gradually respond faster to a fixed stimulus order than to a random order. Moreover, when participants are practicing with a particular stimulus order and, hence, response order and are then confronted with a random order, their responding suddenly slows down. This demonstrates that participants have acquired knowledge about the sequence order. Most studies on implicit sequence learning used keying movements in a serial RT task. As a consequence, many important empirical findings have already been investigated and published about this subject. However, little research has investigated the development of sequential skills when more complex movements serve as sequence elements. Consequently, little is known about the interaction between sequence control and control of aiming movements. Therefore, this dissertation will extend research on the serial RT task by using aiming movements rather than key press movements.

The present chapter will review the state of the art with respect to research on aiming movements, sequences of aiming movements, the serial RT task, implicit learning and awareness. Subsequently, Chapters 2 through 6 will present empirical results of studies that addressed the mechanisms underlying implicit and explicit sequence learning with the serial RT task. Finally, in Chapter 7 the most important findings of the studies in this thesis will be discussed and a general framework will be presented that describes mechanisms of implicit and explicit sequence learning with aiming movements.

1.2 Aiming movements

Aiming movements are simple goal-directed movements such as pointing towards a certain person at a photograph or grasping an apple from a fruit-dish. These movements have been studied extensively since the seminal work of Woodworth (1899) more than a century ago. Woodworth studied the simple task of moving a pencil back and forth, from one position to another. Participants were asked to make these movements at different rates that were specified by a metronome. Woodworth was especially interested in the contribution of vision to aiming movements. Therefore, besides the manipulation of movement velocity, he had participants execute simple hand movements in two different conditions: one condition with the eyes open and one with the eyes closed.

Woodworth's study (1899) showed that as movement slowed, accuracy improved only in the eyes-open condition. Woodworth argued that all aiming movements start with an *initial impulse*; a ballistic movement that covers most of the distance of the aiming movement. He suggested that in an eyes-closed condition movements are entirely preprogrammed and influenced by this impulse. However, in the eyes-open condition, movements are preprogrammed and also corrected with visual feedback control. This visual feedback control was called *current control* by Woodworth. So, already according to Woodworth aiming movements exist of two components: the initial ballistic phase followed by a feedback-based deceleration phase to the final goal position (also called the homing-in phase). The difference between the eyes-open and the eyes-closed condition would be caused by current control. Subsequent studies showed that the time required for the visual feedback to be used is approximately 100 to 200 ms (Keele & Posner, 1968; Zelaznik, Hawkins & Kisselburgh, 1983). Other studies confirmed that visual feedback is very important for the accuracy of aiming movements, especially during the last 25% of these movements (e.g. Elliott, Helsen and Chua, 2001).

Concerning visual feedback in aiming movements, the terms open- and closed-loop are important too. The term *open-loop* refers to the situation in which participants do not receive (visual) feedback of their movements or do not use this feedback during their movements. This corresponds to the ballistic part of the movement. On the contrary, the term *closed-loop* refers to the situation in which feedback is used to correct ongoing movement. Therefore, closed-loop control corresponds to the homing-in part of the movement.

In 1954 Paul Fitts devised a reciprocal aiming task to study how task constraints influence the execution of rapid, goal directed movements of the arm. Participants alternately tapped two rectangular targets with a stylus. The distance between, and the size of, the targets were varied. Fitts discovered a mathematical relationship between movement time, target size, and distance of aiming movements. This relationship turned out to be so robust, that it became known as Fitts' law:

$$MT = a + b \cdot log_2(\frac{2A}{W})$$

In this equation, MT is the movement time, a and b are constants, A denotes the distance between the centre of the targets, and W refers to the width of the targets. The term $log_2\ (2A/W)$ is called the index of difficulty (ID). Nowadays, research investigating aiming movements still refers to Fitts' law (Smits-Engelsman, Van Galen & Duysens, 2002; Augustyn & Rosenbaum, 2005; Buchanan, Park & Shea; 2006). In such studies participants typically move a handle towards a target, or touch (or slide towards) a target with their index-finger or a stylus.

Rosenbaum (1991) describes three models that can explain Fitts' law. The first is the *iterative corrections model.* According to this model, an aiming movement consists of several discrete submovements. This model explains Fitts' law only in terms of the use of visual feedback. On the contrary, the *impulse variability model* assumes that Fitts' law reflects the accuracy of the initial impulse component of an aiming movement and does not assume feedback processing with aiming movement. Both models do not account for all the findings. Therefore, the *optimized initial impulse model* (Meyer, Abrams, Kornblum, Wright & Smith, 1988) is a combination of the iterative corrections model and the impulse variability model, and thus a combination of the ballistic and homing-in phase of an aiming movement.

Meyer et al. (1988) suggested that when people make an aiming movement towards a target as quickly as possible, there are two possibilities. First, the target is hit and the movement is completed. Second, the target is missed and another movement is necessary. This second movement can either hit the target or not. When it is missed again, a third movement must be made, and so on. So, with the second possibility several corrective submovements are required to finally hit the target. Meyer et al. (1988) showed that when participants must reach a target as quickly as possible, the initial movements may be chosen with respect to their likelihood of further correction. Therefore, participants have to find a balance between the distance of the aiming movement and its duration, in order to minimize the total movement time. Fitts' law models this balance and reflects an optimization strategy: participants make a compromise between the initial movement velocity and the time-consuming corrective submovements.

In conclusion, aiming movements usually involve on-line corrections unless the movements must be executed as quickly as possible and there is little or no (time for) feedback processing.

1.3 Sequences of aiming movements

The interest in the human ability to learn and use sequential information for executing motor behavior started about 55 years ago when Lashley (1951) published his famous paper about the problem of serial order in behavior. According to Lashley, actions are organized in a sequential way, and are planned in advance. This holds not only for simple actions like grasping an apple from the table, a goal-directed movement, but also for complex movements like riding a bicycle or language production.

Concerning the planning of actions the equilibrium hypothesis is important. This hypothesis assumes that the motor system first plans goal postures, before executing the required movements (e.g. Jax, Rosenbaum, Vaughan & Meulenbroek, 2003). Therefore, the final positions are important and planning is needed. This is nicely and recognizably defined by Jax et al. (2003, page 11): "The author observed a waiter picking up an upside-down glass and then filling the glass with water. The waiter initially grasped the glass in an awkward position, with the thumb pointing down toward the table. This initially awkward grasp allowed the waiter to hold the glass in a more natural position when the glass was turned right side up. Apparently, the waiter planned his movements with the end position in mind". This quote indicates that, with sequential aiming movements, human beings plan the movements before executing them. The quote also indicates that people prefer a comfortable end posture to a comfortable start posture.

Lashley (1951) argued that actions are hierarchically organized in that the order of movements is determined independently of the nature of those movements. Even actions that seem to be organized in a linear way, meaning that each element in a series of actions seem to provide the excitation of the next, really have an underlying hierarchical structure. For example, preparing a dinner can be said to exist of superordinate goals, basic goals and subordinate goals. One superordinate goal of dinner preparation is preparing a meal. Basic goals for the preparation of a meal are cooking potatoes, cooking vegetables, preparing the salad and so on. Subordinate goals for cooking potatoes are taking a pan from the cupboard, filling the pan with water, lighting the gas, putting the pan on the cooker etcetera. Rosenbaum, Kenny and Derr (1983) demonstrated the use of a hierarchical structure in an experiment in which participants executed rapid keying sequences. In this experiment keying sequences were not only planned hierarchically, during execution they were also controlled hierarchically.

According to Lashley (1951), the production of serial behaviour involves the parallel activation of a set of actions, which together comprise some "chunk", so that responses are internally activated before being externally generated. Sequences of aiming movements that are planned and controlled hierarchically are built up through chunking. With an aiming movement sequence chunking means that people do not gain knowledge by remembering every single movement in a sequence, but by remembering subsequences of two or more movements.

Adam, Paas, Eyssen, Slingerland, Bekkering and Drost (1995) investigated the chunking hypothesis with two-element reciprocal aiming movements. In fact, most studies that focussed on sequential aiming movements discussed two-element responses (e.g. Ricker, Elliott, Lyons, Gauldie, Chua & Byblow, 1999; Helsen, Tremblay, Van den Berg & Elliott, 2004; Khan, Lawrence, Buckolz & Franks, 2006). With two-element responses, participants are required to perform an aiming movement towards a target, come to a short stop, immediately make an aiming movement towards a second target and come to a complete stop. According to Adam et al.'s chunking hypothesis, movements towards small targets require a movement stop, whereas movements towards large targets require a movement reversal without clear stop. In the study of Adam et al. (1995), the chunking hypothesis was supported as it seems that with large targets (60 mm diameter) participants use a single movement pattern consisting of two parts. Apparently, the forward and backward movements in reciprocal aiming are functionally related. On the contrary, with small targets (3 mm diameter) participants use two separate, independent movements. So, only when targets are not too small, sequences of aiming movements are executed as subsequences.

The findings with two-element aiming sequences also show that preparation of the second movement is completed before the first movement is terminated. Furthermore, it seems that what participants see before the first movement can be used to make a movement plan for both targets (Ricker, Elliott, Lyons, Gauldie, Chua & Byblow, 1999). Finally, the study of Khan, Lawrence, Buckolz and Franks (2006) examined whether the influence of response complexity on response times depended on the extent to which aiming movements are programmed before movement initiation or during movement execution. Response complexity was varied by target size (small or large) and number of sequence elements (one- or two-element sequences). The results showed that in the case of more complex responding, participants adopted an online programming strategy, meaning that aiming movements were programmed during movement execution. So, vision and target size influence the moment of planning and control of two-element aiming movements.

The present work focuses on longer sequences of aiming movements instead of one- or two-element target-aiming responses. More specifically, the present studies investigated implicit and explicit sequence learning when the serial reaction time (RT) task includes aiming movements rather than key presses. We were interested in more complex movements, as these are more realistic and probably differently controlled. So, in contrast to earlier studies our interest focused on the serial RT task including aiming movements, the development and use of implicit and explicit learning, and how sequence control and the control of individual aiming movements interact.

1.4 Serial reaction time (RT) task

In 1987 the serial RT task was introduced by Nissen and Bullemer, and it has become one of the most influential paradigms in implicit sequence learning. Buchner and Frensch (1997) suggested that the serial RT task has three properties that cause its popularity. First, it is a model task for simulating event contingencies in the laboratory. Second, it is a simple task which makes it easy to manipulate the experimental conditions. As a consequence the task is usable for addressing many research questions. Third, many researchers regard it as a task which can demonstrate acquisition of complex information without concurrent awareness.

In the typical serial RT task participants sit behind a computer monitor. At the monitor a horizontal row of four circles is visible. An asterisk or dot appears above one of the four positions on the monitor and participants are instructed to react as fast and accurately as possible by pressing the spatially compatible key on a keyboard (e.g. Deroost, Zeeuws & Soetens, 2006; Jiménez & Vázquez, 2005; Keele, Ivry, Mayr, Hazeltine & Heuer, 2003; Kelly & Burton, 2001; Willingham, Greeley & Bardone, 1993). Immediately after the correct key is pressed the asterisk disappears. After a certain time interval the asterisk appears at another position, and so on (see Figure 1.1).

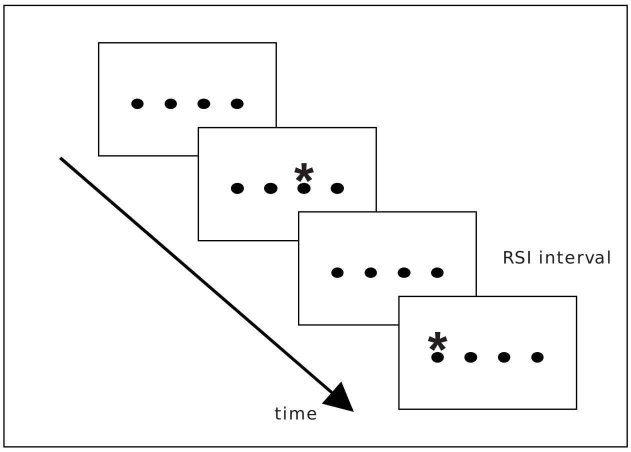

Figure 1.1: Event order in a typical serial RT task. Above one of the dots an asterisk appears and participants press as accurate and fast as possible the spatially compatible key on a keyboard (in this case with the right index finger). The asterisk disappears immediately after the correct key is pressed, and the response to stimulus interval starts. After this interval an asterisk appears above another dot, and so on.

The time interval between disappearance of the asterisk in one position and the appearance in another position is called the response to stimulus interval (RSI). Unknown to the participants, the asterisk appears in a certain order, mostly consisting of 10 to 12 positions in a fixed order. After some practice with the sequence, the asterisk appears randomly in the test block. Sequence learning is demonstrated by increasing response times in this block, when the asterisk suddenly appears randomly, and decreasing response times when the sequence is present again. This can be clearly seen in Figure 1.2. Even when participants are unaware about the order in which the asterisk appears, they appear to learn it.

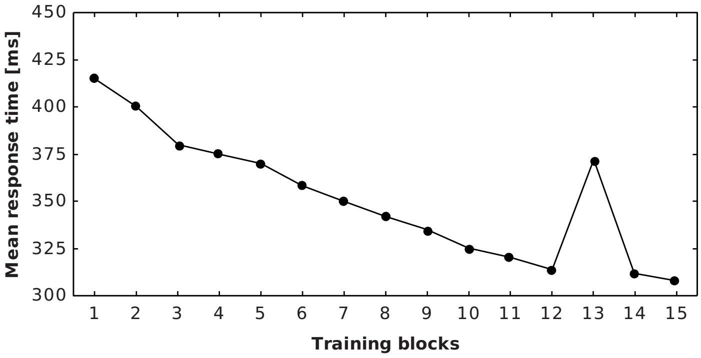

Figure 1.2: Example of typical serial RT task results. In all blocks except block 13 participants performed the same sequence. The line shows that participants' response times decrease as they practice a keying sequence. Sequence learning is clearly demonstrated with the increase in response time in block number 13 in which the asterisk appears in random order.

An important question in this dissertation is whether sequence control and aiming control interfere with each other or whether they function separately. Verwey (2001) proposed the dual processor model for keying sequences. This model assumes that practiced keying sequences are selected and prepared by a cognitive processor and then executed by a motor processor. These two processors can operate in parallel, thereby increasing the execution rate. So, with keying sequences two processors that do not interfere, co-ordinate the execution of the sequences. This might suggest there is also no interference between sequence control and aiming control in the present dissertation. For one thing, however, the study of Verwey did not use the serial RT task; participants executed one out of three discrete sequences with a length of 2, 3, 4 and/or 6 keys. Sequence control and control of aiming movements might be functions of the same processor and the two control levels might interact.

As aiming movements take longer than keying movements, they offer the possibility to study the serial RT task in a different way. For example, it might be possible that participants become more aware of the sequence order, as they need more time to perform the individual movements (Cleeremans & Sarrazin, 2007). This would mean that more explicit sequence knowledge develops. But does this also mean that this explicit knowledge is used? In the next section the phenomenon of implicit learning is explained and discussed.

1.5 Implicit learning

Implicit learning has been defined in many ways. One of the most common definitions of implicit learning says that learning is implicit when people acquire new information without intending to do so, and in such a way that the resulting knowledge is difficult to express (Berry & Dienes, 1993). An everyday example of implicit learning is the acquisition of grammatical rules of the native language by children. When asked, children are unable to explain the rules, yet they do speak their language almost perfectly. So, characteristics of implicit learning processes are that they occur in an incidental manner, without the use of intentional strategies (Frensch, 1998; Reber, 1993), and that the acquired rules can not be verbalized (for an overview about implicit learning see: e.g. Seger, 1994; Cleeremans, 1997). Various empirical procedures have been developed to study whether learning can take place without awareness. The most well-known examples are artificial grammar learning (Reber, 1967, 1989), sequence learning (Nissen and Bullemer, 1987), and dynamic system control (Berry & Broadbent, 1984, 1988).

According to Reber (1993), explicit and implicit learning differ in terms of five characteristics. First, explicit learning is affected by disorders like amnesia, while implicit learning is not (robustness). Second, explicit learning is much affected by age or developmental level, while implicit learning is little affected (age independence). Third, there are large individual differences with explicit learning, while these are small with implicit learning (variability). Fourth, in the case of explicit learning performance is affected by IQ, while it is relatively unaffected with implicit learning (IQ independence). Finally, explicit systems are mainly found in humans, while implicit systems are common to most species. The first characteristic is the strongest evidence for a distinction between implicit and explicit learning. Many researchers found intact implicit learning in amnesic patients despite their impaired explicit learning (e.g. Hopkins, Waldram & Kesner, 2004; Reber & Squire, 1998; Vandenberghe, Schmidt, Fery & Cleeremans, 2006).

If implicit and explicit learning are distinct, then what is the relationship between the two? Keele, Ivry, Mayr, Hazeltine and Heuer (2003) distinguished between two neurocognitive sequence learning systems. The multidimensional system is able to learn implicitly as well as explicitly and requires attention. The unidimensional system is only able to learn implicitly and operates outside of attention. According to Keele et al. (2003), these two learning systems can operate in parallel. Indeed, Willingham and Goedert-Eschmann (1999) argued that implicit and explicit learning both develop in parallel. In the present dissertation, we assessed whether implicit and/or explicit sequence knowledge can still be used in a new situation in which the sequence order is still the same. That is, we investigated the effect of manipulating target size and RSI on the accessibility of implicit and explicit sequence knowledge.

1.6 Awareness

Awareness is the knowledge or understanding that people gain through their perception and/or action, and their reaction to it. Below, the focus will be on two issues. First, why do some participants become aware of the order in the serial RT task and others do not? Second, how are implicit and explicit sequence learning measured in the serial RT task?

The first issue is important for the studies in this dissertation, as the individual differences in awareness offered the possibility to divide participants into different awareness groups and to study implicit and explicit sequence learning with aiming movements. In the literature at least five potential causes of individual differences in awareness are mentioned. The first one is *working memory span* or working memory capacity (Dominey, Lelekov, Ventre-Dominey & Jeannerod, 1998; Feldman Barrett, Tugade & Engle, 2004). In his famous paper "The magic number seven; plus or minus one", Miller (1956) showed that the immediate memory span was determined by number of "chunks" rather than number of items. A chunk is an integrated piece of information, where remembering one part of it will help you remember the next. Memory span as measured in terms of items can be increased by increasing the number of items in each chunk. Chunks possibly play a role in our studies too: When participants recognise the sequence order, they might use this awareness to remember the sequence as chunks of elements (Jiménez, 2008; Koch & Hoffmann, 2000a). For example, the sequence 643521436152 in which the numbers 1 to 6 refer to six sequence elements, might be executed as four subsequences of three elements (respectively 643, 521, 436 and 152) or as two subsequences of six elements (respectively 643521 and 436152).

A second cause of awareness differences among humans is *personality*

(Norman, Price & Duff, 2006). It was shown that the personality measure of 'openness to feelings' influenced both learning and awareness in the SRT task. Third, fourth, and fifth, *cognitive speed*, *intelligence* and *age* appeared to play a role in the individual differences of awareness. A study by McGeorge, Crawford and Kelly (1997) showed that individual differences in the development of awareness are large and that these differences are caused by intelligence and age. Intelligence is related to cognitive speed, in that people with high scores on intelligence tests are also fast at tests of cognitive speed. In conclusion, some participants become aware of the order in a serial RT task, while others do not, due to the individual differences in at least: working memory span, certain personality features, cognitive speed, intelligence and age.

Distraction and observation are interesting factors that seem to play a role in awareness and might be related to individual differences in awareness. Earlier studies that used a secondary task showed that attention can not be divided without affecting implicit or even explicit learning (e.g. Nissen & Bullemer, 1987; Curran & Keele, 1993; Schmidtke & Heuer, 1997; Shanks & Channon, 2002; Shanks, Rowland & Ranger, 2005). Jiménez and Méndez (1999) also investigated the role of attention in implicit sequence learning. In three experiments participants executed the serial RT task under single or secondary task conditions. Their results indicated that a secondary task manipulation barely affected sequence learning, even though selective attention to the predictive dimensions was necessary.

Kelly and Burton (2001) examined whether observation plays a role in awareness. In their study half of the participants executed a keying sequencing task, while the other half was watching. These "observers" were asked to watch both what happened on the screen and keyboard, as they would have to perform this task later. Kelly and Burton concluded that observational learning is not important in awareness. However, other studies (Heyes & Foster, 2002; Song, Howard & Howard, 2008) examined observational motor learning with the serial RT task and showed that participants were able to aquire information about the sequence order by watching another participant executing the task.

The second issue in this section concerns the measurement of explicit sequence learning in the SRT task. In most experiments awareness is measured with an awareness questionnaire after participants conducted the SRT task. This questionnaire mostly exists of a free-recall, a cued-recall and/or a recognition task.

After completion of the SRT task, participants are typically asked "if they noted anything special about the task" (e.g. Shanks, Green & Kolodny, 1994; Willingham, Nissen & Bullemer, 1989). This is a free-recall question and depending on whether participants noticed the stimulus order or not, they are then asked to describe the order in which the stimuli appeared during the task.

The recognition task was introduced by Perruchet and Amorim (1992) as a more sensitive means for measuring explicit knowledge. In their study, participants were asked to rate whether they recognised 4-element sequences as parts of the originally used 10-element sequence that they had practiced.

Serial RT experiments often use the cued-recall generate task introduced by Nissen and Bullemer (1987). In this task, participants are presented with each element within the sequence and are asked by means of a key press to predict the next element of a sequence. Destrebecqz and Cleeremans (2001) used a novel application of the process dissociation procedure (PDP) of Jacoby (1991). Instead of one, they used two generation tasks: one performed under inclusion instruction and the other under exclusion instruction. The inclusion generation task was comparable to the generation tasks that were used before and described above. In the exclusion generation task participants were also asked to generate a sequence, but here they were instructed to avoid the reproduction of sequential regularities of the trained sequence. When participants perform (parts of) the correct sequence in the exclusion condition, this can only reflect implicit sequence knowledge. Destrebecqz and Cleeremans argued that the use of PDP in sequence learning is a useful tool to unravel implicit and explicit sequence learning. In one experiment in this dissertation we used a paper version of this procedure. However, it appeared not useful in our version of the serial RT task with aiming movements: Participants found it too difficult and it showed no results whatsoever. Therefore we do not mention this procedure in this dissertation any further.

There has been a debate about whether the methods in the explicit knowledge questionnaire really measure the knowledge of a participant in the serial RT task or not. Shanks and St. John (1994) discuss prediction tests and recognition tests as measures of awareness, as they believe that there is no convincing evidence of implicit learning in the serial RT task. In prediction tests, participants are instructed to predict the next target in a sequence. Importantly, no rapid responses are required in this test. In recognition tests, participants are presented with sequences which either have been part of the practiced sequence or not. Participants are instructed to decide whether these sequences were part of the practiced sequence or not.

Shanks and St. John (1994) argued that there are at least three reasons to doubt that implicit knowledge underlies performance in the serial RT task. First, in the prediction task participants predict the next response, whereas in the serial RT task participants respond to the current stimulus. So, when implicit knowledge plays a role in the serial RT task, one would expect that participants make response errors in the prediction task as the response required in this task is different from the one that is performed in the serial RT task. However, no significant evidence was found for this, suggesting that participants used explicit knowledge in the serial RT task. Second, suppose that implicit knowledge is measured with the recognition test. In this case one would expect shorter response times in the recognition test for sequences that have been part of the practiced sequence than for sequences that were not. Again, no evidence was found for this (e.g. Perruchet & Amorim, 1992). Third, three different versions of the recognition task did not show significantly different results (Willingham, Greeley & Bardone, 1993). In one version of the recognition task participants responded to test sequences the way they did during the practice phase and then executed the recognition task. The second version of the recognition task differed from this, in that participants now only observed the stimulus sequence before executing the recognition task. The third group of participants saw the stimulus sequence in digits instead of screen locations. The latter two versions of the recognition task rules out perceptual fluency as the basis of judgments, but no difference was found between the three versions of the task. The conclusion of Shanks and St. John (1994) is that there is no convincing evidence of implicit learning in the serial RT task.

Jackson and Jackson (1995) also wondered whether the explicit knowledge questionnaire really measures the knowledge of participants in the serial RT task or not. They distinguish between two forms of sequence knowledge: serial and statistical knowledge. Serial knowledge is knowledge about the sequence order. Statistical knowledge is knowledge about the probability of different transitions between adjacent sequence elements. They argued that the sequence knowledge of participants as measured in the questionnaire can be independent of the knowledge that participants have of the statistical structure of the sequence. However, Jiménez, Méndez and Cleeremans (1996b) addressed two issues in the work of Jackson and Jackson (1995) that they consider as problematic. First, the distinction between serial and statistical knowledge is a misleading one, because both kinds of knowledge can be acquired in the same way. Therefore, Jiménez et al. (1996b) propose instead that all sequence knowledge is statistical. Second, Jiménez et al. (1996b) suggest that it is better to use probabilistic sequences, rather than deterministic onces as Jackson and Jackson (1995) did, to explore the assessment of explicit knowledge. One reason for this is that deterministic sequences cannot contain many combinations of sequence elements, which makes reliable statistical analyses more difficult. Also, because of the short sequence length there is a possibility that participants learn the sequence (better) during the generation task and thus during the measuring of explicit sequence knowledge.

In the present dissertation we used a paper version of the knowledge questionnaire after the aiming movement task had ended. The questionnaire consisted of different parts. In the free recall part participants were asked whether they noticed anything special during the aiming movement task. The next part told participants that there had been a certain order in which they executed the aiming movements and they were asked to reproduce this order, or fragments of it. The recognition part of the questionnaire showed the participants (fragments of) sequences and they were asked whether they executed them during the aiming movement task. So, despite the commentary on the questionnaire, we decided to use it. Not only is it easy to use, but more importantly the questionnaire requires participants to use another response modality, as explicit sequence knowledge is characterized by its availability to other systems in the brain (Cleeremans & Sarrazin, 2007). This availability is caused by three properties of the explicit representations: the stability in time, the strength and the distinctiveness. The stability in time is the duration that representations can be maintained active during processing. The strength of representations is the number of processing units that are involved in representations. The distinctiveness of representations is the extent of overlap between representations of similar instances. Cleeremans and Sarrazin thus suggest that the availability of representations to conscious awareness depends on the quality of these three properties. So, we used a paper version of the knowledge questionnaire, as the availability of representations to conscious awareness, and thus explicit sequence knowledge, can be measured this way.

In conclusion, due to individual differences some participants become aware of the sequence order in the serial RT task and others do not. This offers the possibility to examine both implicit and explicit sequence knowledge in an aiming movement version of the serial RT task in a single group. In our studies explicit sequence knowledge is measured by means of a questionnaire. Our interest in this dissertation will focus on differences between sequence control and aiming movement control for aware and unaware participants. The most important question is: Do sequence control and aiming movement control interfere and is this different for aware and unaware participants? Based on earlier research, the introduction in Chapter 2 suggests that there are three possibilities for interference between sequence control and aiming movement control: no interference, limited interference or full interference. The target size and the length of the RSI are important variables to find out whether there is no, limited or full interference between sequence control and aiming movement control.

1.7 Overview of the studies

Sequence learning is one of the most prevalent forms of human (and animal) learning and it therefore has become a very popular topic of interest. In this dissertation, the issue of interference between control of sequences and of individual aiming movements is addressed in five empirical studies. These studies might teach us how human beings execute aiming movement sequences and to what extent they are able to transfer the sequential information to new situations. The practical importance lies in everyday life: for example, how do we use sequential knowledge when we cook a meal or play a piece of music?

The first study in Chapter 2 includes two experiments in which the target size, the response to stimulus interval (RSI) and the sequence order were varied. The research question is whether implicit and/or explicit sequence knowledge can develop and be applied during the execution of aiming movements. Because a random sequence can not easily be compared with the practice sequence (Reed & Johnson, 1994) as reversals occur more often in random than in fixed sequences (Vaquero, Jiménez & Lupiáñez, 2006), a comparable experiment was executed in Chapter 3 with new sequences instead of random ones. There were more improvements in Chapter 3 compared to Chapter 2. The most important improvement concerned the use of second order conditional (SOC) sequences. The distinguishing mark of SOC sequences is that improvement during practice of these sequences can not be caused by learning that certain elements or transitions within the sequence occur more often than others (Shanks & St. John, 1994). Also, Chapter 3 used shorter RSIs during both the practice and test phase, to find out how sequence knowledge develops over time. Finally, we used an intermediate target diameter in Chapter 3 compared with the experiments in Chapter 2. One of the reasons for using an intermediate target diameter was that with the small diameter in Chapter 2 participants made many errors.

Subsequently, in Chapter 4, half of the participants practiced the sequence of 12 elements and the other half practiced the same sequence with an extra, repeating element after each element of the sequence (hence, 24 in total). This study investigated whether implicit and explicit sequence learning occurs also when a repeating element in between the regular elements is used. Moreover, the study examined whether this knowledge is transferable to a situation in which the repeating element is removed (if present during practice) or inserted (if absent during practice). The response times in Chapter 2 had suggested that participants without awareness moved their hand to the centre of the imaginary circle on which the targets were positioned in order to quickly reach each next target, whereas participants with awareness went straight to the next target. As sequence learning was found for all participants, the development and expression of implicit sequence knowledge seemed not affected by moving the hand to some fixed, central position. Therefore, we examined in Chapter 4 how development and use of implicit and explicit sequence learning is affected by tapping one specific target located at the centre of the sequence targets, every time a regular sequence target has been hit.

Until now, only a few studies that investigated sequence learning (e.g., Wilde & Shea, 2006) focused on the ability of participants to transfer learned movement sequences to conditions that differ from those experienced during practice. More specifically, the sequence order remains unchanged, but the spatial requirements of the sequence are changed. This has practical importance, because in everyday life people are confronted with executing learned movement sequences to environmental conditions with different spatial requirements. For example, an organ-player may be confronted with a keyboard that has a different key size than the keyboard he is used to practice and play on. Theoretically the transfer of movement sequences to lay-outs of different sizes is important because it may teach us how movement sequences are stored, executed and controlled. Therefore, in Chapter 5 the applicability of schema theory of Schmidt (1975) and Fitts' law in our serial RT paradigm are examined. We wondered whether both implicit and explicit sequence learning of aiming movements would be influenced by target size and thus by the complexity of individual movements.

In the last of the five empirical study chapters, Chapter 6, participants practiced a sequence and then executed a rotated or point-mirrored version of the practiced sequence during the test phase. Earlier studies had suggested that the transfer of implicit sequence knowledge towards mirrored versions of the original stimuli orders would be easier than the transfer of explicit sequence knowledge. Therefore, the expectation would then be that the transfer of sequence knowledge to rotated or point-mirrored sequences is larger for implicit than explicit sequence knowledge. However, the earlier studies used keying sequences and we wondered whether this result also holds for aiming movement sequences.

Finally, in Chapter 7, the results of the five studies are reviewed and discussed.

Chapter 2

An aiming movement version of the serial reaction time task: Explicit knowledge can be acquired but not applied during movement execution

2.1 Abstract

In two experiments participants practiced a serial reaction time task with aiming movements. In Experiment 1 participants practiced with a response stimulus interval (RSI) of 200 ms, and in Experiment 2 with an RSI of 0 ms. In both experiments participants then performed in an identical test phase involving manipulation of target size, RSI, and sequence order. The results of Experiment 1 indicated that the development of implicit and explicit knowledge sequence is not disturbed by concurrent execution of aiming movements, that implicit knowledge can be applied during execution of the preceding aiming movement, and that explicit knowledge can hardly be applied before the preceding movement had been completed. The results of Experiment 2 confirmed these findings and showed that applying explicit knowledge with fast movements needs to be learned. Participants classified as aware and unaware showed qualitatively different effects of RSI and target size, supporting the validity of the paper awareness classification test in demonstrating that aware participants use a qualitatively different type of knowledge than unaware participants.

2.2 Introduction

Implicit learning, the ability to acquire knowledge in the absence of the capacity to verbally express what was learned, has been an area of research for over 35 years. An experimental task that is well-suited to study the acquisition and use of implicit knowledge is the serial reaction time (RT) task. This task was introduced by Nissen and Bullemer (1987) and is still used regularly. In the typical serial RT task, a stimulus is presented at one of four horizontally arranged locations. Participants respond to each stimulus by pressing the spatially compatible key on a keyboard. After a brief response to stimulus interval (RSI), the next stimulus is presented and the ensuing response is given, and so on. In the experimental condition, stimuli cycle through a fixed series of 10 to 12 locations while participants are not informed of this regularity. Sequence learning is indicated by a difference in response times in the experimental condition compared with those in a (pseudo-)random order condition.

People who are unable to describe or reproduce the sequence without stimuli being presented are assumed to have little or no explicit knowledge of the sequence. Yet, the fact that, after improvement in fixed sequence blocks, their performance reduces in a (pseudo-)random block indicates that they did acquire implicit knowledge of the sequence. Implicit knowledge is characterized by the fact that learning is robust to forgetting, is often hyperspecific and bound to surface characteristics. In contrast, explicit knowledge is characterized by the fact that it can be applied flexibly and in various ways (Dienes & Berry 1997). That is, people with awareness of the sequence are not only able to give a verbal expression of the sequence, but they are able also to prepare individual movements in the sequence before these are cued (Curran, 1995; Eichenbaum, 1999; Willingham, Nissen & Bullemer, 1989). This flexibility suggests that, in contrast to implicit knowledge, explicit knowledge should be defined as knowledge that can be translated from one code to another (Reber & Squire, 1998; Rhodes, Bullock, Verwey, Averbeck & Page, 2004; Squire, Knowlton & Musen, 1993).

The general consensus is that the inability to give a verbal account of the sequence can not be taken good evidence for the absence of explicit knowledge (e.g., Cleeremans, Destrebecqz & Boyer, 1998; Jackson & Jackson, 1995). More compelling evidence for implicit knowledge being separate from explicit knowledge has been reported recently in studies (a) measuring physiological correlates of preparation (Eimer, Goschke, Schlaghecken & Stürmer, 1996; Rüsseler, Hennighausen, Münte & Rösler, 2003), (b) comparing amnesic and healthy participants (Reber & Squire, 1998), and (c) using advanced behavioural procedures to assess awareness (Destrebecqz & Cleeremans, 2001). Importantly, in keying versions of the serial RT task development and use of explicit knowledge have been found to reduce with shorter RSIs whereas development and use of implicit knowledge were not affected (e.g. Destrebecqz & Cleeremans, 2001; Frensch, Buchner & Lin, 1994; Frensch & Miner, 1994; Willingham, Greenberg & Thomas, 1997; but see Miyawaki, 2006; Shanks, Wilkinson & Channon, 2003).

The present study assessed sequence learning in the serial RT task when the individual movements consist of aiming rather than typing movements. To our knowledge, only a few studies used aiming movements with this task (Corr, 2003; Dominey, Lelekov, Ventre-Dominey & Jeannerod, 1998). However, these did not explicitly study the effect that aiming movements have on development and use of explicit and implicit sequence knowledge. Still, this paradigm is interesting as it may reveal whether or not processes involved in the development and use of implicit and explicit knowledge occur during execution of aiming movements.

The finding that the learning and expression of explicit sequence knowledge is affected by RSI, whereas that is not the case with implicit knowledge (Destrebecqz & Cleeremans, 2001), might imply for the present study that the development and use of explicit sequence knowledge is more vulnerable to concurrent movement execution than the development and use of implicit sequence knowledge. The present study independently varied RSI and target size (and therewith movement time) to examine whether that would affect the development and use of implicit and/or explicit sequence knowledge in the aiming version of the serial RT task.

As to the effect of target size and RSI on development and use of sequence knowledge, three possibilities can be distinguished. First, the *time availability hypothesis* (cf. Garcia-Colera & Semjen, 1988) assumes that there is no interference between execution of individual movements and sequence control, and that the available time between successive movements is the delimiting factor in the development and use of sequence knowledge. Hence, sequence knowledge will be developed and used better when targets are smaller because movements take longer.

Second, sequence learning in the serial RT task has been found to reduce when participants perform a secondary task (e.g., Curran & Keele, 1993; Frensch, Wenke & Rünger, 1999; Jiménez, Méndez & Cleeremans, 1996a; Shanks & Channon, 2002). Likewise, the execution of an aiming movement may have the same hampering effects as a secondary task on learning and expression of sequence knowledge. Therefore, the *limited-interference hypothesis*, assumes that the extent that sequence knowledge can be developed and applied depends on the difficulty of the aiming movement: When targets are small and aiming requires processing resources (due to closed loop control involving correction on the basis of on-line processed feedback information, e.g., Meyer, Abrams, Kornblum, Wright & Smith, 1988; Pratt & Abrams, 1996), sequence processing will not occur during execution of aiming movements and development and use of sequencing knowledge will depend heavily on RSI. With large targets, however, aiming is open loop and may allow concurrent processing of sequence knowledge so that the duration of RSI is not important with large targets.

Third, the *full-interference hypothesis* asserts that sequence knowledge can never be developed and applied before a movement has been completed (just like visual information is not processed during an eye movement; e.g., Sanders & Houtmans, 1985; Sanders & Rath, 1991). Consequently, development and application of sequence knowledge is determined by RSI and target size is irrelevant.

We carried out two serial RT experiments that examined whether (implicit or explicit) sequence knowledge can develop and be applied during execution of aiming movements by independently manipulating RSI and target size. In Experiment 1 we had two groups of participants practice a 12-item aiming movement version of the serial RT task with the typical 200 ms RSI separating successive aiming movements. Six white circular targets were positioned equidistantly on an imaginary circle. Participants were instructed to hit the target that turned (partly) red. They were not informed about the repeating pattern in which the targets appeared. The area to be hit was small (diameter 9 mm) for one group, and large (diameter 24 mm) for the other. In a subsequent test phase there were three blocks with fixed and three with random sequences, each with RSIs of either 0, 200, or 400 ms. Participants always tapped the same target sizes as during practice. Experiment 2 was virtually the same as Experiment 1 but involved practice with 0 RSIs to examine whether the development of explicit knowledge reduces without RSI (as indicated by Destrebecqz & Cleeremans, 2001 for sequential keying). When sequence knowledge is used during execution of a movement (time availability hypothesis), RSI may be less important for performance with smaller than with larger targets due to the longer time available before a small target is hit, unless the available movement time is sufficient even with large targets. If, however, execution of aiming movements interferes with the preparation of forthcoming movements there are two possibilities. First, there is no concurrent processing at all (full interference hypothesis) and effects of RSI on learning and performance are unaffected by target size. Second, concurrent processing is possible with large targets only (limited interference hypothesis) so that RSI has larger performance effects for the smaller than the larger targets. Comparing the results of participants with full and with little or no awareness of the sequence will be taken to show whether the effects hold for implicit or explicit sequence knowledge.

2.3 Experiment 1

2.3.1 Method

PARTICIPANTS

Thirty-six right-handed participants, 18 men and 18 women, aged 20-42 (mean 30), took part in the experiment. They had never participated in a sequence learning experiment before.

TASK

Six white, round areas of 24 mm were presented on the black background of a touch sensitive computer monitor. These areas represented potential targets and were positioned equidistantly on an imaginary circle of 216 mm diameter. One target was on top of the imaginary circle and the other five were positioned at subsequent angles of 60° each, relative to the centre of the imaginary circle (Figure 2.1).

Participants were randomly assigned to one of two different practice groups: the *9 mm target group* and the *24 mm target group*. When a ring at the outside of a target area turned red, (leaving the 9 mm centre white, Figure 2.1), participants were instructed to hit the target area with an accessory pen as fast and as accurately as possible. Participants in the 24 mm target group were instructed to hit either the red or the white area of the target, whereas participants in the 9 mm target group were told to just hit the 9 mm diameter white target area in the centre. So, even though the stimulus was identical for both groups, the response requirements differed. After the target was hit, the target immediately turned white again and, after a certain RSI, the ring of the next target turned red. This continued until the end of the block. When participants missed the target area, a green pixel appeared at the location touched and they were instructed to try hitting the target again.

Targets were either presented in a random order, or they followed a fixed sequence of twelve targets. The sequence involved only ambiguous transitions (i.e. second order conditionals, Schvaneveldt & Gomez, 1998): A target could only be predicted by the preceding two stimuli and never by the preceding one alone. Six participants cycled through the basic sequence 315236451426. Targets on the right side of the display were sometimes occluded by the right hand that tapped targets. Therefore, five other groups of six participants cycled through rotated versions of the basic sequence (426341562531, 531452613642, and so on) in order to distribute possible effects of occlusion by the hand across all sequence positions.

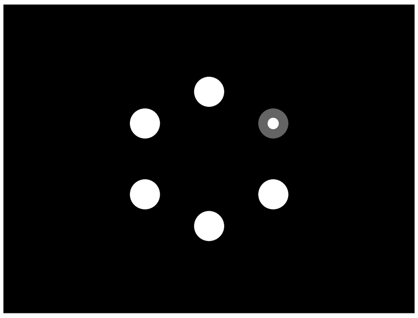

Figure 2.1: Example of the touch screen appearance during a trial with the red circle as target. The 9 mm group had to hit the inner (white) circle, while the 24 mm group had to hit the white or red area.

PROCEDURE

The experiment consisted of fifteen blocks of 108 trials (i.e. individual responses) each, and it took about 1.5 min to complete a block. In the first block, the targets appeared in a random order to prevent awareness due to immediately searching for structure (Willingham, 1999). This also helped participants to get familiar with the experimental setting. In the next eight blocks, together making up the practice phase, the sequence involved a fixed stimulus order. Hence, the sequence was practiced in total for 8 x 9 = 72 sequence repetitions. In the practice phase of Experiment 1 RSIs were always 200 ms. Subsequently, participants executed the test phase. The first three test blocks included a random order of targets. Each block included a different RSI of 0, 200 or 400 ms. The last three test blocks involved fixed sequences with 0, 200 or 400 ms RSIs in the different blocks. The three random blocks in the test phase that differed with respect to RSI, were counterbalanced across participants, as were the subsequent three fixed sequence blocks.

The four-part awareness questionnaire that was filled out by the participants following the last block relied heavily on recognition, as forced-choice is considered a proper way of assessing awareness (Cleeremans et al., 1998; Jiménez et al., 1996a; Shanks et al., 2003; Stadler, 1989; Willingham et al., 1989). This recognition test was deliberately on paper: If participants had explicit knowledge about the sequential order, it was assumed that they would be sufficiently flexible in the use of sequence knowledge to perform the awareness test on paper. In part A of this test, participants were asked whether they had noted anything special. Part B informed the participants that there had been a fixed sequence and they were asked to draw the sequence (or parts of it) in a figure already containing the six targets. An example was presented on the same page. In part C participants were offered 36 pictures. Each picture showed the six circular targets with their sequential order indicated by numbers and arrows. Eighteen pictures included four successive targets; twelve showed six successive targets; and six included the complete twelve target sequences used for the six participant groups. Participants indicated below each picture whether they had executed that sequence or fragment and their certainty on a 100-point rating scale. Finally, in part D, the participants were presented with the six alternative sequences actually used by participants with the rotated versions of the basic sequence. They were told they had executed one of these and were asked which one. Each part of the questionnaire was read and filled out only after the previous part had been completed. Once filled out, corrections and changes were not allowed.

APPARATUS

Stimulus presentation and response registration were controlled with Micro Experimental Laboratory (MEL version 2.0) software on a 333 MHz Pentium-based PC. The targets were displayed and tapped on a 17 inch IIYAMA Vision Master MF8617E monitor producing a 640 x 480 pixel VGA image, with a ClearTek capacitive touch-sensitive layer that senses the location of a tap with a resolution of 1024 x 1024 pixels. Taps were carried out with the accessory pen. The interval between the moment the screen was tapped and the moment the target colour changed varied between 9 and 27 ms due to system delays.

The touch monitor was mounted screen up in a hole in a table and tilted backwards (table-screen surface angle 30°). The participants sat in a dimly illuminated room in front of this touch sensitive display. A chin and forehead rest was used to ensure a constant viewing distance of 45 cm between the position of the eyes and the screen surface and to make sure that parallax problems of the screen due to different head positions were minimal. The eyes looked downward at an angle of about 45° onto the screen surface.

DATA ANALYSIS

Analyses concerned average response times and error proportions per participant and block. Response time was defined as the time between the onset of a target and the moment the target was hit, and included the time to perceive target onset (if not already anticipated) and the time to move there, but excluded RSI. The first two trials of each block, trials in which targets were not hit accurately, and the two trials after the latter were excluded from the response time analyses. Also, trials were eliminated from the analyses when response times deviated more than three times the standard deviation from the block average across participants within the diameter group. The latter procedure removed approximately 2% of the data in every condition.

2.3.2 Results

AWARENESS GROUPS

Participants were divided into three awareness groups on basis of the questionnaire results. The most important test for determining awareness was part D in which participants were classified first on whether or not they had correctly recognized their sequence out of the six alternatives. It turned out that precisely half the participants (18) had not recognized their sequence and the other half had. Subsequently, the participants were rank ordered within each of these two groups, according to the number of correct transitions they had made in the reproduction part (part B) of the questionnaire. If participants had the same number of transitions, their certainty score on part C determined their rank order. The twelve participants with the least correct transitions, who were worst in recognizing their 'own' sequence or parts of it, were classified as the unaware group. Similarly, the twelve participants with the most correct transitions, who were best at recognizing their sequence or parts of it, were classified as the aware group. The remaining twelve participants were classified partially aware. Table 2.1 presents the details of each of the three groups. As awareness was similar in the 9 and 24 mm target groups, these results do not support the time availability and limited interference hypotheses for development of explicit knowledge that assume that awareness is affected by target size (via movement time).

A subsequent Kruskal-Wallis ANOVA on rank orders for certainty of accepting or rejecting the given sequences (part C of the questionnaire), showed that median certainty rating increased with awareness, correct sequences $H(2, n = 36) = 6.6, p < .05$; incorrect sequences $H(2, n = 36) = 8.8, p < .05$.

Table 2.1: Characteristics of the three awareness groups in Experiment 1 according to the questionnaire results and the numbers of participants in each group.

Awareness group	Participants with spontaneous remark on order (Part A)	Mean number of correct transisions (total 12) (Part B)	Median certainty of identifying the correct sequence (scale 0 - 100) (Part C)	Median certainty of identifying the incorrect sequences (scale 0 - 100) (Part C)	Participants in 9 mm group (n = 18)	Participants in 24 mm group (n = 18)
unaware (n = 12)	n = 4 (33%)	0.33 (range 0 - 3)	25	28.8	n = 5 (28%)	n = 7 (39%)
partially aware (n = 12)	n = 8 (67%)	2.58 (range 3 - 5)	62.5	46.3	n = 7 (39%)	n = 5 (28%)
aware (n = 12)	n = 12 (100%)	7.75 (range 6 - 12)	81.3	77.5	n = 6 (33%)	n = 6 (33%)

PRACTICE PHASE

Response times of the fixed and random sequence were classified as a function of short, medium and large distances (see Figure 2.1). For each participant, the random sequence analysis included only response times associated with movements between targets that occurred in the fixed sequence too. (Notice that systematic differences in response order between fixed and random sequences are argued to hamper conclusions on sequence learning in the serial RT studies. However, these differences like more reversals (Vaquero, Jiménez & Lupiáñez, 2006) do not affect the effects of RSI and target size here).

Figure 2.2 shows the response times of the three awareness groups across all 15 blocks. A Block (8: blocks 2-9) x Awareness (3) x Group (2: 9 vs. 24 mm target size) x Distance (3: small, medium, large) ANOVA was carried out on the response times obtained in the eight practice blocks. The main effects showed that awareness was associated with a higher execution rate, $F(2, 30) = 4.1$, $p < .05$, that movements towards smaller targets were slower, $F(1, 30) = 40.0$, $p < .001$, that movements of the short distance were slowest $F(2, 60) = 19.9$, $p < .001$, and that participants improved during practice, $F(7, 210) = 54.1$, $p < .001$. The suggestion in Figure 2.2 that awareness was associated with larger improvement in blocks 2-9 was significant, $F(14, 210) = 4.5$, $p < .001$. There were no indications that learning rate interacted with target size, $F(7, 210) < 1$, $p > .20$, or with both target size and awareness, $F(14, 210) < 1$, $p > .20$.

The analysis also showed an important Awareness x Distance interaction, $F(4, 60) = 4.6$, $p < .01$. Subsequent planned comparisons used to scrutinize this interaction indicated that responses of aware participants were slower with the largest than with the intermediate distance, $F(1, 30) = 11.0$, $p < .01$. This is what one would expect when participants go straight from one target to the next. In contrast, unaware participants were slower with small than with medium and large distances, $Fs(1, 30) > 19.6$, $ps < .01$, which is in line with the notion that participants did not know what target to expect next, and went to the centre of the area with the six targets after hitting a target.

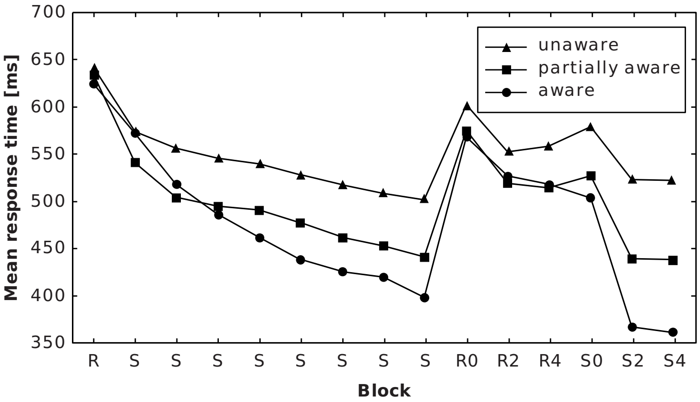

Figure 2.2: Mean response times of Experiment 1 in all blocks for the three awareness groups. The first nine blocks made up the practice phase, and the last six blocks formed the test phase. R = random order, S = sequence order, and 0, 2 and 4 denote RSIs of 0, 200 and 400 ms. The order within each set of three test blocks (R0-R4 and S0-S4) was counterbalanced across participants.

Since, from a theoretical perspective, the partially aware group was not particularly interesting as it most likely involved participants with explicit knowledge of just a few short and more conspicuous fragments (Anastasopoulou & Harvey, 1999; Cajochen, Knoblauch, Wirz-Justice, Krauchi, Graw & Wallach, 2004; Van der Graaf, De Jong, & Wijers, 2001; Perruchet & Vinter, 2002), we excluded the partially aware group from the analyses reported below. However, further analyses, not reported here, confirmed our expectation that performance of this group always lay in between those of the aware and unaware groups.

TEST PHASE

Figure 2.3 shows response times in the various test conditions. Response times were analysed with a Group (2: 9 vs. 24 mm target size) x Awareness (2: unaware vs. aware) x Sequence (2: random vs. fixed) x RSI (3: 0, 200, 400 ms) x Distance (3) ANOVA with Group and Awareness as between subject variables. All main effects appeared significant (*ps* < .01, for Distance = .05).

Figure 2.3 shows that (relative to the random sequence) aware participants executed the fixed sequence faster than unaware participants and that this benefit increased with RSI. These findings were supported by a significant Awareness x Sequence interaction, $F(1, 20) = 31.7, p < .001$, and an Awareness x Sequence x RSI interaction, $F(2, 40) = 12.4, p < .001$. Planned comparisons showed that the advantage of the fixed over the random sequence was significant for aware participants in each individual RSI condition, $Fs(1, 20) > 28.1, ps < .001$. For unaware participants this advantage was only significant in the 400 ms RSI condition, $F(1, 20) = 5.2, p < .05$, although the other two RSI conditions showed the same trend of this advantage, $Fs(1, 20) > 3.5, ps < .07$. While for aware participants the advantage of fixed over random sequences was significantly larger in the 200/400 ms RSI than in the 0 ms RSI condition, $F(1, 20) = 47.8, p < .001$ (200 and 400 ms did not differ), for unaware participants this advantage did not change significantly with RSI, $F(1, 20) = 0.4, p > .20$. Even with no RSI the advantage of fixed over random sequences was greater for aware than for unaware participants, $F(1, 20) = 5.7, p < .05$ (left panel of Figure 2.3). So, with the 12 unaware participants there seems to be a moderate advantage of fixed over random sequences due to implicit knowledge, which was not affected by RSI, while with the 12 aware participants there was a larger advantage due to explicit knowledge with no RSI, which increased when RSI was 200 ms (but did not further increase when RSI became 400 ms).

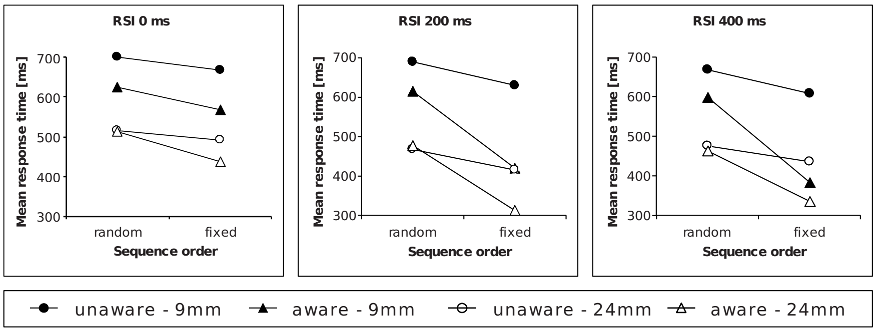

Figure 2.3: The results of the test phase of Experiment 1 are depicted here. They concern the mean response times of the aware and unaware participants in the random and fixed sequence as a function of 9 versus 24 mm target group and RSI 0, 200 and 400 ms.

Different target sizes were used to examine the effect of movement difficulty on implicit and/or explicit sequence learning. The Group x Awareness interaction was not significant, *F*(1, 20) = 2.7, *p* > .10, indicating that the difference in target size (i.e, processing complexity and/or available time) did not influence aware and unaware participants differently. This was confirmed by planned comparisons showing that for both aware and unaware participants, the benefits of fixed over random sequences did not differ for the 9 and 24 mm target size groups, *Fs*(1, 20) < 2.2, *ps* > .15. So, it seems that target diameter did not have an effect on implicit and/or explicit sequence knowledge.

In line with the analysis of practice phase data, significance of the Awareness x Distance interaction, *F*(2, 40) = 4.8, *p* < .05, suggests that aware participants were fastest on short distances whereas unaware participants were slowest on short distances (Figure 2.4). Planned comparisons confirmed that aware participants executed the three movement distances equally fast in the random sequence condition, *Fs*(1, 20) < .1, *ps* > .20, whereas in the fixed sequence condition their response times were longer on the large than the medium, *F*(1, 20) = 5.3, *p* < .05, or short distance, *F*(1, 20) = 2.8, *p* = .05 (one-tailed). In addition, planned comparisons confirmed that only in the fixed sequence condition, unaware participants were slower on short distances than on medium, *F*(1, 20) = 8.2, *p* < .01, and long distances, *F*(1, 20) = 4.9, *p* < .05. However, these two effects were not present with an RSI of 0 ms, *Fs*(1, 20) < 3.5, *ps* > .07.

The possibility that awareness would be associated with a generally better movement skill was not borne out. A Group (2) x Awareness (2) x Block (2) ANOVA on the response times of Block 1 and the block in the test condition that involved a random target presentation with 200 ms RSIs too, did not show that aware participants were faster than unaware participants in these two random blocks, $F(1, 20) = 1.6, p > .20$.

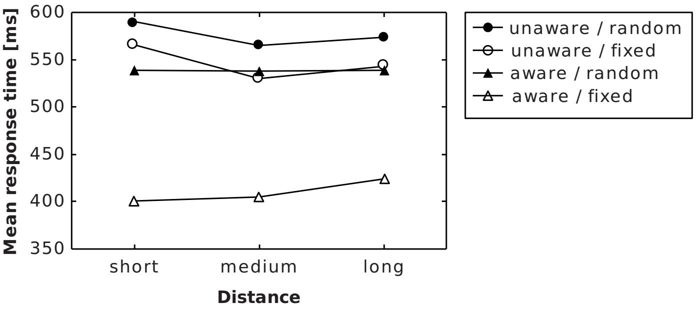

Figure 2.4: Mean response times in the test phase of Experiment 1 for aware and unaware participants with short, medium and large distance movements as a function of fixed versus random sequences.

ERRORS

Error proportions were subjected to arcsin transformations to obtain more normal data distributions (Winer, Brown & Michels, 1991). According to a Group (2) x Awareness (3) x Block (8) ANOVA on errors in the practice phase, participants made relatively few errors in the 24 mm target condition (1.5%) as compared to the 9 mm target condition (8.6%), $F(1, 30) = 95.5, p < .001$. Arcsin transformed error percentages in the test phase were analysed with a Group (2) x Awareness (3) x Block (6) ANOVA. It showed that participants made more errors in the random blocks (5.8%) than in the fixed blocks (4.6%), $F(1, 30) = 9.5, p < .01$. There were no significant effects of awareness or RSI on errors.

2.3.3 Discussion

The present results confirm that executing aiming movements does not change the typical findings of aware and unaware participants obtained with the keying version of the serial RT task (Corr, 2003; Dominey et al., 1998). The finding that there were similar proportions of aware, partially aware and unaware participants in the 9 and the 24 mm target conditions indicates that the development of explicit knowledge was not affected by the difficulty (and time) of the movements. In itself, this rejects the limited interference hypothesis for the development of explicit knowledge, as well as the time availability hypothesis that assumes that awareness develops more easily with smaller targets (because more time is available). Performance in the practice phase shows that learning rate was higher for aware than unaware participants suggesting that aware participants were able to increasingly apply their explicit knowledge, but the practice data do not indicate whether the development and application of explicit knowledge occurred during execution of the aiming movements, or once each movement had finished (i.e. during RSI).

In the test phase, unaware participants were faster on the fixed than the random sequence with 0 RSIs but they did not benefit from longer RSIs. So, implicit knowledge was probably applied even when there were no RSIs, that is during movement execution. This supports the no-interference hypothesis for application of implicit knowledge. In contrast, aware participants benefited more from their sequence knowledge than unaware participants at 0 RSI, and became even faster when RSI was 200 ms (increase to 400 ms did not further change this). These data are largely in line with the full interference hypothesis for applying explicit knowledge during RSI, though some of the explicit knowledge seems to have been applied any way during the preceding movement. In terms of an additive stage model, the forthcoming movement may have been selected during execution of the preceding movement, while actual programming may have had to be postponed until the previous movement had been completed (Verwey, 1995, 2001).

Analyses of response times differences as a function of movement distance show that aware participants took longer to move across longer distances with the fixed sequence in both the practice and the test phase (but not with the random sequence). They probably went straight from one target to the next. In contrast, unaware participants were slowest on the shortest movements in the practice phase and the fixed sequence of the test phase, suggesting that they did not immediately move to the next target. Instead, they may have moved to a location useful for moving to any next target, such as the centre of the area with the six targets. This explanation is supported by the finding that moving back to the adjacent target (i.e. across the smallest distance) actually took longer than moving to targets at larger distances. This difference between aware and unaware participants is important as it confirms in a new way results of other studies showing that explicit knowledge improves performance by preparing oncoming movements even before the next target is shown (e.g., Destrebecqz & Cleeremans, 2001; Rüsseler et al., 2003).

2.4 Experiment 2

Destrebecqz and Cleeremans (2001, 2003) concluded that practising without RSI in the keying version of the serial RT task does not prevent learning of implicit sequence knowledge, but that RSI is necessary for the development of explicit sequence knowledge (for alternative views see Shanks et al., 2003; Wilkinson & Shanks, 2004). Experiment 1 indeed showed that the application of explicit knowledge is limited with 0 RSI. To examine for the present task whether explicit sequence knowledge develops only when each movement is followed by an RSI, Experiment 2 replicated Experiment 1 with the exception that RSI was 0 ms during the practice phase. If learning explicit knowledge takes place just during RSI, the 0 RSI in the practice phase should prevent development of awareness.

2.4.1 Method

Thirty-six right-handed participants, 9 men and 27 women, aged 18 - 25 (mean 22), took part in the second experiment. As in Experiment 1 they had never participated in a sequence learning experiment before. The task, procedure, apparatus and data analysis in Experiment 2 were identical to those in Experiment 1, except that practice in Experiment 2 included 0 RSIs.

2.4.2 Results

AWARENESS GROUPS

Based on the paper awareness questionnaire results, participants were divided into three awareness groups according to the same classification criteria as described in Experiment 1. Again half of the participants (18) recognised the executed sequence. Therefore, the absolute level of awareness was not different in both experiments. The details of each awareness group are in Table 2.2. This table shows that, again, awareness was similar in the 9 and 24 mm target groups. This confirms the conclusion in Experiment 1 that the slower movements associated with 9 mm targets did not cause more (or less) explicit sequence knowledge than the faster movements associated with the 24 mm targets. Hence, the 0 ms RSI in Experiment 2 during practice did not affect the development of explicit knowledge.

A Kruskal-Wallis ANOVA on rank orders for certainty of accepting or rejecting the given sequences showed that median certainty rating increased with awareness, correct sequences $H(2, n = 36) = 12.9, p < .01$; incorrect sequences $H(2, n = 36) = 17.4, p < .01$.

Table 2.2: Characteristics of the three awareness groups in Experiment 2 according to the questionnaire results and the number of participants in each group.

Awareness group	Participants with spontaneous remark on order (Part A)	Mean number of correct transitions (total 12) (Part B)	Median certainty of identifying the correct sequence (scale 0 - 100) (Part C)	Median certainty of identifying the incorrect sequences (scale 0 - 100) (Part C)	Participants in 9 mm group (n = 18)	Participants in 24 mm group (n = 18)
Unaware (n = 12)	n = 5 (42%)	1.42 (range 0 - 3)	37.5	52.8	n = 7 (39%)	n = 5 (28%)
partially aware (n = 12)	n = 8 (67%)	2.92 (range 1 - 5)	43.8	56.9	n = 5 (28%)	n = 7 (39%)
Aware (n = 12)	n = 12 (100%)	6.50 (range 3 - 11)	93.8	91.3	n = 6 (33%)	n = 6 (33%)

PRACTICE PHASE

Figure 2.5 shows the mean response times for all 15 blocks of the experiment. Like in Experiment 1 the partially aware group was always in between the aware and unaware group and was not included in the analyses below. Response times of the eight practice blocks were analysed with a Block (8: blocks 2-9) x Awareness (2: aware vs. unaware) x Group (2: 9 vs. 24 mm target size) x Distance (3: small, medium, large) ANOVA. Main effects showed that response times associated with smaller targets were slower than those associated with larger targets, $F(1, 20) = 80.4$, $p < .001$, that participants improved during practice, $F(7, 140) = 44.6, p < .001$, and that aware participants were faster than unaware ones, $F(1, 20) = 4.3$, $p = .05$. There was no indication that block interacted with target size, $F(7, 140) < 1.3$, $p > .20$, or with target size and awareness, $F(7, 140) < 1.0$, $p > .20$. These findings are equal to those in Experiment 1, except that in Experiment 2 awareness did not interact with block, $F(7, 140) < 1.0$, $p > .20$, or distance, $F(2, 40) < 1$, $p > .20$. So, aware participants did not improve in the use they made of explicit knowledge during practice.

The Awareness x Distance interaction was not significant, because this time all participants had the shortest response times with the small distances and the longest response times with the large distances, $F(2, 40) = 6.1$, $p < .01$. This suggests that in the practice phase of Experiment 2 both groups of participants went straight to the next target. This is reasonable given that the next target lit immediately after the previous one was being hit (i.e. RSI = 0 ms), and moving first to some central location was not useful for any participant.

To examine the effect of the 0 ms RSI on performance, the practice phases of Experiments 1 and 2 were compared with an Experiment (2) x Block (8: blocks 2-9) x Awareness (2) x Group (2: 9 vs. 24 mm target size) x Distance (3: small, medium, large) ANOVA. It confirmed that aware participants improved much less in Experiment 2 than in Experiment 1, whereas improvement was not different for unaware participants. This was indicated by an Experiment x Block x Awareness interaction, $F(7, 280) = 3.9$, $p < .001$. Apparently, the 0 RSI condition in the practice phase affected the expression of explicit but not of implicit sequence knowledge.

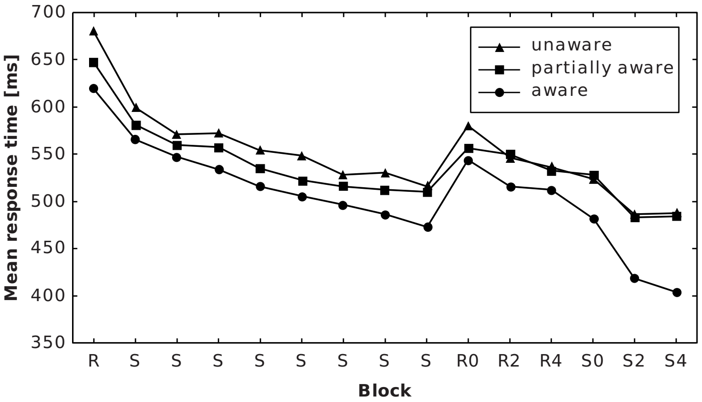

Figure 2.5: Mean response times of Experiment 2 in all blocks of the three awareness groups. See explanation of figure 2.2.

TEST PHASE

The results of the six test conditions are depicted in Figure 2.6. The response times were analysed with a Group (2: 9 vs. 24 mm target size) x Awareness (2: aware vs. unaware) x Sequence (2: random vs. fixed) x RSI (3: 0, 200, 400 ms) x Distance (3: small, medium, large) ANOVA. The main effects of Group, Awareness, Sequence and RSI were significant (*ps* < .01) while the main effect of Distance was not significant, *F*(2, 40) < 1, *p* > .20. Figure 2.6 shows the same general picture as Figure 2.3, suggesting that the elimination of RSI during practice in Experiment 2 had not affected learning as much as it had as compared with Experiment 1.

Figure 2.6 shows that aware participants had a similar pattern of benefits as in Experiment 1: a small benefit at 0 ms RSI that rose as RSI increased to 200 and 400 ms. These findings were supported by two interactions: an Awareness x RSI x Diameter interaction, *F*(2, 40) = 4.5, *p* < .05, supporting that aware participants benefited more from longer RSIs than unaware participants in the 9 mm condition, and an Awareness x Sequence x Diameter interaction, *F*(1, 20) = 4.8, *p* < .05, indicating that aware participants benefited more from the fixed sequence than unaware participants in the 9 mm condition. According to planned comparisons, the advantage of the fixed over the random sequence was significant for both aware and unaware participants in each individual RSI condition, *Fs*(1, 20) > 6.8, *ps* < .05.

For aware participants in the 9 mm condition, the advantage of fixed over random sequences was larger in the 200/400 ms RSI than in the 0 ms RSI condition, $F(1, 20) = 5.1$, $p < .05$ (200 and 400 ms did not differ), implying that expression of explicit knowledge was limited at RSI 0 ms and increased when RSI was 200 and 400 ms. Indeed, planned comparisons showed a benefit of aware over unaware participants with an RSI of 200 and 400 ms and a diameter of 9 mm, $Fs(1, 20) > 4.1$, $ps < .05$. In contrast, unaware participants did not profit from a longer RSI, $F(1, 20) < 1$, $p > .20$.

Interestingly, and supported by Awareness x RSI x Diameter and Awareness x Sequence x Diameter interactions ($ps < .05$), for aware participants the benefit in the 9 mm target condition was greater than in the 24 mm target condition, $F(1, 20) = 7.0$, $p < .05$. This suggests that explicit knowledge was more useful when targets were small and that applying explicit knowledge with fast movements (24 mm) needs to be learned (see Figure 2.6). Planned comparisons showed that this effect for aware participants reached significance only in the 400 ms RSI condition, $F(1, 20) = 8.3$, $p < .01$.

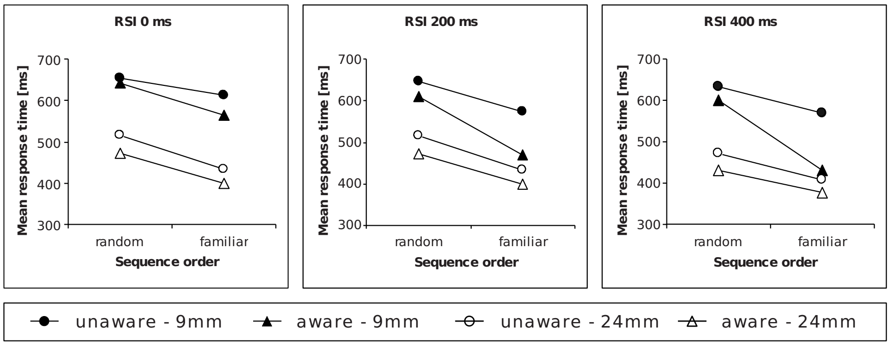

Figure 2.6: The results of the test phase of Experiment 2 are here depicted. They concern the mean response times of the aware and unaware participants in the random and fixed sequence as a function of 9 versus 24 mm target group and RSI 0, 200 and 400 ms.

The test phase of Experiment 2 was compared with the (identical) test phase of Experiment 1 in an Experiment (2) x Group (2: 9 vs. 24 mm target size) x

Awareness (2: aware vs. unaware) x Sequence (2: random vs. fixed) x RSI (3: 0, 200, 400 ms) x Distance (3: small, medium, large) ANOVA. It showed two significant interactions suggesting a difference between the two experiments: an Experiment x RSI, $F(2, 80) = 5.4$, $p < .01$ and an Experiment x Sequence x Aware interaction, $F(1, 40) = 8.8$, $p < .01$. Subsequent planned comparisons indicated that the Experiment x RSI interaction was significant for aware participants, $F(2, 40) = 5.5$, $p < .01$, but not for unaware participants, $F(2, 40) < 1.0$, $p > .20$. Together with comparison of Figures 2.2 and 2.5, these effects show that aware participants were faster in the fixed blocks of Experiment 1 than of Experiment 2, whereas this was not found with unaware participants. Further planned comparisons on each of the three RSI conditions indicated that in the fixed blocks of the test phase aware participants were faster in the RSI 200 ms condition of Experiment 1 than in Experiment 2, $F(1, 40) = 4.4$, $p < .05$. Yet, the same analyses of the 0 and 400 ms RSI condition demonstrated no difference between the two experiments, $Fs(1, 40) = 1.8$, $ps > .18$. Because participants in Experiment 1 had been practicing with an RSI of 200 ms, it seems aware participants need practice with 200 ms RSIs before they can properly use their explicit knowledge.

Finally, in Experiment 2 a Group (2) x Awareness (2) x Block (2) x Distance (3) ANOVA was conducted on the response times of Block 1 and the comparable random (RSI 0) block in the test condition. Like in Experiment 1, aware participants appeared not significantly faster in the random blocks than unaware participants, $F(1, 20) = 3.7$, $p > .07$.

ERRORS

An overall Group (2) x Awareness (3) x Block (15) ANOVA on arcsin transformed errors demonstrated that participants made less errors in the 24 mm target group (3.8%) than the 9 mm target group (9.9%), $F(1, 30) = 161.4$, $p < .001$. According to a Group (2) x Awareness (3) x Block (6) ANOVA of the test phase, participants made more errors in the random blocks (7.3%) than in the fixed blocks (6.6%), $F(1, 30) = 11.9$, $p < .01$.

2.4.3 Discussion

The main reason to perform Experiment 2 was determining whether explicit knowledge develops during practice also when successive movements are not separated by an RSI. The awareness data clearly showed that development of awareness in Experiment 2 was similar to that in Experiment 1. This is confirmed by the general advantage of aware over unaware participants in the test phase.

Examination of the practice data of Experiment 2 shows that, even though aware participants were generally faster than unaware participants, this time learning rate was not higher for aware than for unaware participants, as in Experiment 1. Furthermore, the expression of explicit knowledge was less with the 200 ms RSI in Experiment 2 than in Experiment 1 (but not so with the 0 and 400 ms RSIs). Together with the finding that awareness was not different in both experiments, these findings indicate that the presence of explicit knowledge in itself is insufficient for a performance advantage of aware participants with aiming movements: Application of explicit knowledge needs to be practiced too.

In contrast to Experiment 1, 9 mm participants benefited more from awareness than 24 mm participants. For one thing, this confirms the rejection of the limited-interference hypothesis which states that execution of movements to 9 mm targets would interfere more, and not less, with development and use of sequence knowledge. In itself, this finding is in line with the time-availability hypothesis for explicit knowledge that assumes that the longer duration of movements to 9 mm targets is used for applying sequence knowledge. However, the middle frame of Figure 2.6 suggests that when interference plays no role, the 380 ms movement time plus 200 ms RSI (= 580 ms) provides enough time for 24 mm participants to apply explicit knowledge. In the 400 ms RSI condition aware 24 mm participants even had available about 800 ms and they were still not able to apply explicit knowledge. Therefore, we would like to argue that the limited advantage of aware over unaware 24 mm participants is not caused by the fact that explicit knowledge could not be applied during the preceding movement (which time they did not need any way in the RSI 400 ms condition), but rather by the fact that aware participants in Experiment 2 had not learned to apply their explicit knowledge during RSI to further increase movement speed. In addition, there may have been a ceiling effect in that movements to 24 mm targets were already fast and did not profit from additional RSI. This reasoning receives support also from the finding that, in contrast to Experiment 1, Experiment 2 showed no effect of distance on response time at all, neither for aware nor for unaware participants in the test phase. This confirms that aware participants did not even apply their explicit knowledge for preparing forthcoming movements when the RSI was basically long enough to do so.

2.5 General discussion

The goal of the present study was to determine whether implicit and/or explicit sequence knowledge can be learned and applied during aiming movements of varying precision and duration. First of all, both experiments confirmed our expectation that, like with the keying version of the serial RT task, awareness varied amongst participants and aware participants had generally shorter response times on the fixed sequences than unaware participants. As both experiments showed similar proportions of aware and unaware participants in the 9 and 24 mm target size groups, the development of explicit knowledge appears affected neither by movement duration nor by 0 RSI during practice.

The test phases of both experiments showed that, irrespective of target size, unaware participants had full benefit of their (implicit) sequence knowledge already with 0 RSIs. It seems they did not benefit any further from longer RSIs. This demonstrates that implicit sequence knowledge can be applied during the preceding movement, thus supporting the the notion that there is no interference between execution of aiming movements and the expression of implicit knowledge. These data are in line with findings in the keying version of the serial RT task that implicit knowledge develops and can be applied even when RSI is 0 (Destrebecqz & Cleeremans, 2001, 2003).

In both experiments aware participants had only a limited advantage over unaware participants with 0 RSI but this advantage increased with the longer RSIs (except for aware 24 mm participants in Experiment 2). This limited advantage with 0 RSI suggests, first, that explicit knowledge can hardly be applied during execution of the preceding movement. The indication for the small advantage of aware participants with 0 ms RSI is in accordance with findings by Verwey (1995, 2003b) suggesting that movement execution allows concurrent selection of movements but not programming. The distance analyses in Experiment 1 show that aware participants used their knowledge to immediately move to the next target, which would suggest that movements had been selected during the preceding movement. So, the present results generally support the full-interference hypothesis for application of explicit sequence knowledge (beyond some initial preparatory processes). A second important finding in this respect is that aware 24 mm participants in Experiment 2 showed little benefit of their explicit knowledge when RSI in the test phase increased whereas those in Experiment 1 did. As both experiments differed only with respect to RSI during practice, these data indicate that development of explicit sequence knowledge is itself not sufficient for beneficial effects of explicit knowledge because the rapid application of explicit knowledge needs to be learned too. In contrast to participants in Experiment 1, those in Experiment 2 had not learned this and were therefore not able to fasten the already rapid movements found with 24 mm targets.

The finding in Experiment 2 that explicit knowledge developed even with 0 ms RSI stands in sharp contrast with results obtained with the keying version of the serial RT task indicating that development of explicit knowledge is hampered by 0 ms RSIs (Destrebecqz & Cleeremans, 2001, 2003). This difference may be attributed to various methodological differences between the present and previous studies, but the most obvious one is that Destrebecqz and Cleeremans (2001, 2003) used keying sequences while we used aiming movement sequences. Indeed, Destrebecqz and Cleeremans (2001, 2003) argued that there must be sufficient time between successive responses in order for explicit knowledge to develop. The present research suggests that this time need not be an RSI but that movement time may provide this time as well.

On basis of the present data, we argue that the present data show that questionnaires may indeed be suitable to demonstrate that performance is based on different types of knowledge, that is, implicit versus explicit sequence knowledge. This is indicated by the qualitatively different ways in which sequence knowledge was used. That is, aware participants needed RSI to optimally use their sequence knowledge while unaware participants did not. Aware participants seem to have anticipated forthcoming movements whereas unaware participants merely responded (essentially turning the task into a generation task, e.g. Destrebecqz & Cleeremans, 2003; Shanks & Perruchet, 2002; Wilkinson & Shanks, 2004), and aware participants benefited to an increasing extent of the 200 ms RSIs while unaware participants did not. In fact, the present data support the idea that implicit knowledge is in a code that can be used with little processing, whereas explicit knowledge requires substantial processing that requires too much resources to occur during movement execution (e.g., Rhodes et al., 2004).

In conclusion, the present experiments demonstrate that implicit and explicit sequence knowledge develop even while aiming movements are carried out. Implicit sequence knowledge can be applied during movement execution, but application of explicit knowledge largely has to await completion of the preceding aiming movement. Even those who developed explicit sequence knowledge seem to require practice before they can rapidly apply that knowledge. The qualitatively different ways in which implicit and explicit knowledge are used supports the notion that awareness questionnaires distinguish between qualitatively different types of sequence knowledge.

Chapter 3

Does the application of both implicit and explicit knowledge improve with longer RSIs in an aiming movement version of the serial reaction time task?

3.1 Abstract

The present experiment investigated in an aiming movement version of the serial RT task whether implicit and explicit sequence knowledge are applied during or after executing individual aiming movements. Participants practiced a fixed aiming movement sequence with a response to stimulus interval (RSI) of 100 ms. In the test phase they performed in six different test blocks: the practiced sequence or a new one, factorially combined with an RSI of either 0, 100 or 200 ms. Participants with explicit sequence knowledge appeared to execute the practiced sequence faster than participants without explicit sequence knowledge (but with implicit knowledge). However, as opposed to an earlier study, performance increased with RSI for both aware and unaware participants, suggesting that both explicit and implicit knowledge can not be fully applied during execution of the preceding aiming movement. Several explanations for this beneficial effect of RSI in unaware participants are discussed.

3.2 Introduction

Sometimes people are able to tell in detail about the movements they make in a highly skilled task, in which case we talk about explicit knowledge. Often these movements can not be verbalized, and we talk about implicit knowledge (Berry & Dienes, 1993; Chambaron, Ginhac, Ferrel-Chapus & Perruchet, 2006; Cleeremans, Destrebecqz & Boyer, 1998; Seger, 1994). Reber (1967) investigated implicit learning for the first time with an artificial grammar learning paradigm. In this paradigm participants were able to later discriminate novel grammatical from non grammatical strings, but at the same time they were unable to verbalize the grammar rules. Reber therefore concluded that participants had developed implicit knowledge of the abstract rules of the grammar.

Today, implicit learning is investigated especially with the serial reaction time (SRT) task (Nissen and Bullemer, 1987). In the typical SRT task, participants see four horizontally aligned stimulus locations on a computer screen. When one of them lights up participants are to respond by pressing a corresponding key. Following a response to stimulus interval (RSI) of, typically, 200 ms, the next stimulus is presented requiring the next response, and so on. Without participants being informed of it, stimuli often follow a fixed order of 12, and then start again. The longer response times found when the order is random, pseudo-random or new rather than as practiced are taken to indicate that participants have learned the practiced sequence. Despite their improved performance many participants are not able to indicate the order of the elements in the sequence and are said to have implicit sequence knowledge.

In an earlier study we found indications that implicit knowledge can be learned and applied during movement execution in an aiming movement version of the SRT task in which participants hit targets on a touch sensitive screen in a particular order (Ter Schegget & Verwey, 2009a). In contrast, explicit knowledge appeared to develop during the execution of aiming movements, but the application of explicit knowledge to determine the next movement appeared to largely await completion of the preceding aiming movements. In that study, RSI during practice was 200 ms in a first, and 0 ms in a second experiment. Subsequently, participants performed in six test blocks. Three of these involved the same key pressing order as participants had just practiced, but these blocks differed with respect to the RSI used: 0, 200 and 400 ms. In the other three blocks the sequence order was random and RSI was also either 0, 200, or 400 ms. The practice results indicated that for unaware participants improvement was not different with the 0 and 200 ms RSIs, while aware participants improved much more with an RSI of 200 than of 0 ms. In the test conditions performance improved as RSI became longer with aware participants while performance was unaffected by RSI with unaware participants. These results indicated 1) that implicit and explicit sequence knowledge can develop also while aiming movements are being carried out; 2) that implicit knowledge on a forthcoming aiming movement can be applied during execution of the preceding movement; but 3) that explicit knowledge can hardly be applied before the preceding movement has been completed and is applied mainly following movement completion (i.e., during RSI).

The first aim of the present study was to see whether we could replicate the effects of the RSI manipulation with an improved version of the earlier two experiments. The most important improvement concerned the use of second order conditional (SOC) sequences. Such sequences are characterized by the fact that improvement can not be caused by learning that certain elements and certain transitions between elements occur more often than others (Shanks & St.John, 1994). We were interested whether the results would be different from, or were generalizable to, SOC sequences that were not used in the earlier two experiments. In those experiments, every element occurred twice in a sequence and therefore, the number of alternative responses given a particular response was two for the participants who knew the sequence. In the present study every element occurred three times in the sequence, making up three alternative responses. Thus, although the number of elements was lower in the present study than in the earlier study (four instead of six), the number of alternative responses given a preceding target was higher. It might be that (implicit) learning is stronger with fewer alternative responses (earlier study), because in this case sequence knowledge is based on more simple associations.

Another improvement concerned the control sequence. The earlier study involved as control sequence a fully random sequence, which may not be appropriate as control sequence for assessing the degree of sequence learning (Reed & Johnson, 1994). Reversals like 232, for example, occur more often in random than in fixed sequences and are relatively slow (Vaquero, Jiménez & Lupiáñez, 2006). This could suggest more learning with a random than a new sequence as control condition. Therefore, in the present study we used new sequences with the same structure as the practiced sequence rather than random ones. So, in the earlier study (implicit) learning might seem stronger as a consequence of the random sequences that were used.

The target diameters were also changed compared to the earlier study of Ter Schegget and Verwey (2009a). The earlier study used a large target diameter of 24 mm and a small one of 9 mm. In the present study the target diameter was 16 mm. We wanted to use an intermediate target diameter (16 mm) in a design with more power to find out whether unaware participants benefit with an 0 ms RSI and an intermediate target diameter. Also, participants in the earlier study made many errors with the 9 mm target diameter (8.6% in Experiment 1 and 9.9% in Experiment 2).

The second aim concerned the role of RSI. The previous study showed no difference between the 200 and 400 ms RSIs. In the test phase we now used RSIs of 0, 100 and 200 ms to be better able to see how application of explicit knowledge develops over time. The Ter Schegget and Verwey (2009a) study suggested that the more aware participants used the 200 ms RSI in the practice phase of Experiment 1 to move their hand immediately to the next target, whereas less aware participants seemed to first move their hand to a strategic location from where the distance to all target areas was equal (which is the centre of the imaginary circle on which the targets were positioned). In line with this interpretation, no such difference was found between aware and unaware participants when RSI was 0 ms in the practice phase (Experiment 2) because in that situation all participants were able to immediately see the next target and move their hand irrespective of awareness. We were interested to see whether 100 ms RSI during practice would suffice for aware participants to also immediately move to the next target before it was presented.

In short, the goal of the present study was to replicate with an improved version of the serial RT task the findings of the previous study that suggested a qualitative difference between the ways in which implicit and explicit sequence knowledge are handled with an aiming version of the serial RT task.

3.3 Experiment

3.3.1 Method

PARTICIPANTS

All 36 right-handed participants (18 men and 18 women) who performed in the present experiment had normal or corrected to normal vision. Their mean age was 27.6 ± 5.6 years, and none of them had participated in an (aiming movement) sequence learning experiment before. They were paid € 6 for participation.

TASK

Four white circles with a diameter of 32 mm, together forming an imaginary diamond with equal sides and equal diagonals, were presented on the black background of a touch screen (see Figure 3.1). A circle became target when a red ring with the same external diameter as the circle and a 16 mm inner diameter was presented on top of the (white) circle. The distance between the circle centres was 70 mm for adjacent and 99 mm for opposite circles. The participants were instructed to hit the white centre of the red ring with a stylus (in their right hand) as fast and accurately as possible. After the target area was properly hit, the red ring disappeared, the white circle was presented again, and the red ring was presented on top of another circle. The response to stimulus interval (RSI, indicating the time between hitting a target and onset of the next target) was 100 ms during practice, and 0, 100, or 200 ms during the test phase.

We used second order conditionals (SOCs) in the present experiment implying that every element occurs three times in the sequence, one element is followed by every possible other element once (e.g., “24”, “23” and “21”), and elements are never repeated (Reed & Johnson, 1994; Schvaneveldt & Gomez, 1998). An example of such a sequence is 234214131243. In total eight different SOC sequences were used in the present experiment. Every participant executed five different SOC sequences: one in the first block, another one in Blocks 2-9 and the test phase (i.e., the familiar sequence), and three as new sequences in the test phase. In the practice Blocks 2-9 (and in the test block with the familiar sequence) we used four different sequences for four groups of participants to distribute effects of stimulus occlusion by the right hand across all sequence elements. That is, one group of participants executed the basic sequence 124132342143 and three other groups executed a rotated version of this basic sequence (namely 231243413214, 342314124321 and 413421231432). The sequence of the first block and the three new sequences of the test phase were also balanced across participants: A particular sequence was used for nine of the 36 participants in the first block, for nine others in the first new block of the test phase, etcetera. These four sequences were: 142123413243, 214132431234, 431423213412 and 321243142341.

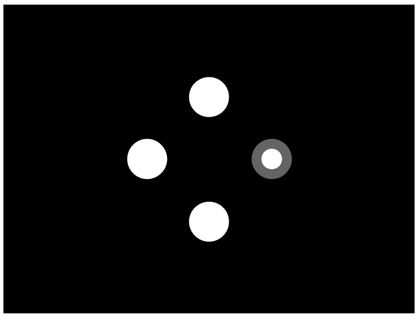

Figure 3.1: Participants saw this image on the touch-sensitive display during the experiment. The target was recognizable by the red outer ring. Participants were to hit the inner white part of the target.

PROCEDURE

Before participants started the height of their chair was adjusted to their length, so they could sit comfortably while leaning their head in the chin- and forehead rest. The participants read the information about the experiment on the screen, and when necessary this was extended with oral explanation. It took the participants approximately one hour to conduct the experiment.

All 16 blocks of the experiment consisted of a 12-element sequence that was repeated nine times within a block, yielding 108 taps per block. Between every two blocks there was a 20 s break. The practice phase started off with a block with one particular 12 element try-out sequence. After this first block participants performed eight blocks containing another 12 element sequence that eventually was repeated (8 x 9 =) 72 times. Next, the six block test phase started. The order of these test blocks was varied across the four groups of participants. Three blocks of the test phase contained the practiced sequence and each of three further blocks another new sequence. The three blocks with familiar and new sequences differed with respect to RSI: 0, 100 (as in the practice phase), and 200 ms. Finally, participants executed Block 16, which was identical to Blocks 2-9 of the practice phase. Participants were not informed about the sequence order, and filled out an awareness questionnaire after the 16th and final block.

The paper awareness questionnaire consisted of four parts and was basically the same as in Chapter 2 (Ter Schegget & Verwey, 2009a). In part A participants were asked to select the best fitting of six descriptions: (1) the order was random; (2) some positions appeared more frequent than others; (3) my hand was inclined to go in a certain direction; (4) the order was often predictable; (5) the same order appeared more than once; and (6) the same order appeared throughout the entire experiment. Part B of the questionnaire made clear to the participants that they had carried out a fixed sequence, without mentioning sequence length. The participants were asked to draw this sequence or parts of it on a sheet indicating the four target areas (free recall). An example was provided on the same page. Part C consisted of 12 drawings of possible sequences or parts of it, including the four actually used sequences in the practice phase. The participants wrote down for each of the drawings on a 100 point scale how certain they were that they had or had not executed the indicated sequence. Finally, part D of the awareness questionnaire consisted of a forced choice test and showed four drawings, each one containing one sequence. Participants filled out which one of the four sequences they thought they had executed and how certain they were about this on a 100 point scale.

APPARATUS

The experiment was carried out in a small, dimly illuminated room in the experimental laboratory of our faculty. The experimenter sat behind the control computer, a 333 MHz Pentium-based PC. This computer conducted the experiment with MEL (Micro Experimental Laboratory, version 2.0) software and collected the data. Participants sat behind a table in which a touch sensitive monitor screen was mounted. The monitor was tilted backwards so that the screen surface had an angle of 30° relative to the table surface. The targets were displayed and tapped with a special stylus on this 17 inch IIYAMA Vision Master MF8617E monitor. This so-called touch screen produced a 640 x 480 pixel VGA image, with a ClearTek capacitive touch-sensitive layer that senses the location of a tap with a resolution of 1024 x 1024 pixels. Due to system delays, RSIs also included an additional system delay of 9 to 27 ms. During task performance participants laid their head in a chin- and forehead rest to secure a viewing distance of about 45 cm between the eyes and the touch sensitive screen for every participant.

DATA ANALYSIS

Dependent variables were mean response times and error percentages per participant and block. Response time was the time between the onset of a target and hitting it. A response time was not included in the analyses when it was the first or second response time of a block; the target was not hit correctly (an error); the previous response or the response before was erroneous; or it was an outlier (i.e. > 3 standard deviations above the average within a block across participants). The outliers made up approximately 2% of the response times.

3.3.2 Results

AWARENESS GROUPS

Participants were first divided into two groups on basis of part D of the awareness questionnaire depending on whether they had selected their own sequence from the set of four alternatives. It appeared that 20 participants had selected the sequence they actually carried out, and 16 participants had not. Participants in each group were then rank ordered on basis of their results in part B of the awareness questionnaire (free recall). When two or more participants ended up with the same ranking, the number of correct answers and certainty scores in part C were used to determine the rank order. The 12 participants ranking highest ended up as the aware group, the 12 participants with the lowest rank numbers formed the unaware group. The remaining 12 participants were considered partially aware. Table 3.1 presents the characteristics of the three awareness groups.

Table 3.1: Characteristics of the three awareness groups according to the questionnaire results.

Awareness group	Participants selecting the correct statement in questionnaire (Part A)	Mean number of correct transitions in sequence drawn of 12 (Part B)	Median certainty of identifying the correct sequence (scale 1 - 100) (Part C)	Median certainty of identifying the incorrect sequences (scale 1 - 100) (Part C)
unaware (*n* = 12)	*n* = 4 (33%)	1.58 (range 0 - 3)	39.8	34.8
partially aware (*n* = 12)	*n* = 7 (58%)	3.22 (range 0 - 5)	51.0	47.2
aware (*n* = 12)	*n* = 11 (92%)	7.67 (range 4 - 12)	85.2	73.3

The certainty scores that participants filled out in the awareness questionnaire supported the division of the three awareness groups (see Table 3.1). A Kruskall-Wallis Anova on rank orders for certainty of accepting or rejecting the given sequences (part C of the questionnaire), showed that median certainty rating increased with awareness, both for correct sequences $H(2, n = 36) = 14.9, p < .001$, and incorrect sequences $H(2, n = 36) = 11.8, p < .01$. Incorrect sequences were (parts of) sequences different from the familiar sequence that participants had practiced in Blocks 2-9.

PRACTICE PHASE

Figure 3.2 shows the mean response times obtained in the 16 blocks of the present experiment. It confirms our earlier results with 0 and 200 ms RSI in that awareness with 100 ms RSI was associated with faster improvement and better performance in the last practice block too (Ter Schegget & Verwey, 2009a). As various analyses showed that performance of the partially aware group was always in between the other two awareness groups, the partially aware group was not included in the analyses reported below.

The response times of the eight practice blocks were analyzed with an Awareness (2: aware vs. unaware) x Block (8: blocks 2-9) x Distance (2: small vs. large) ANOVA, with Block and Distance as within-subjects variables. The variable Distance distinguished adjacent from opposite targets (see Figure 3.1). The main effects showed that participants improved during practice, $F(7, 154) = 44.9, p < .001$, that aware participants were faster than unaware ones, $F(1, 22) = 31.7, p < .001$, and that response times with the large distance were longer than those with the small distance, $F(1, 22) = 24.9, p < .001$. The Block x Awareness interaction confirmed that aware participants improved more than unaware ones, $F(7, 154) = 7.2, p < .001$. In contrast to Experiment 1 in Chapter 2, in which participants practiced with a 200 ms RSI, the Distance x Awareness interaction did not reach significance, $F(1, 22) < 1, p > .20$. This suggests that with the present 100 ms RSI aware and unaware participants did not use different movement strategies.

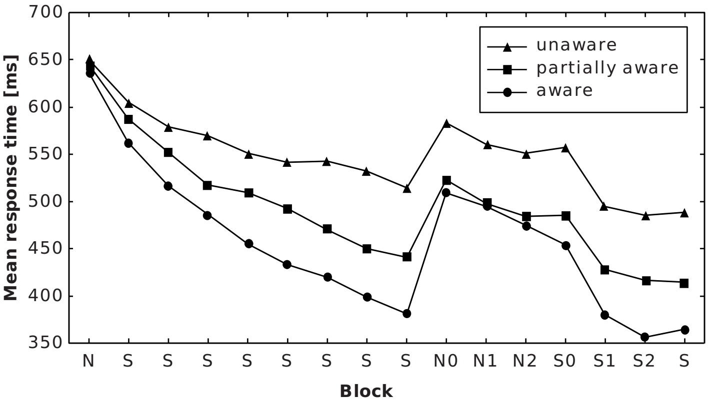

Figure 3.2: Mean response times of the three awareness groups for all 16 blocks in the experiment. The first nine blocks made up the practice phase, and the next six blocks (N0-S2) formed the test phase. The last block (S) was executed before filling in the questionnaire. N denotes that the block contains a new sequence (in each N block another one). S stands for blocks with a fixed order for each participant. The 0, 1, and 2 denote respectively the 0, 100, and 200 ms RSIs. Block order in the test phase was varied across participants.

TEST PHASE

The response times of the test phase were analyzed with an Awareness (2) x Sequence (2: new vs. practiced) x RSI (3: 0, 100, 200 ms) x Distance (2) ANOVA with Awareness as the only between-subjects variable. All main effects appeared to be significant (*ps* < .01). The results of the test phase are in figure 3.3.

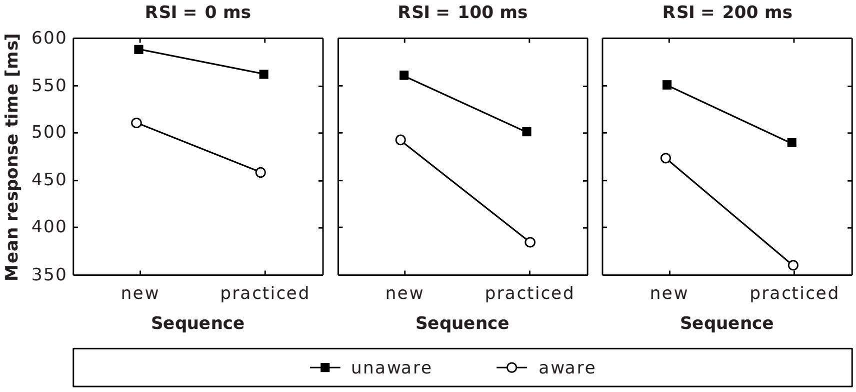

Figure 3.3: Mean response times in the test phase of the aware and unaware participants as a function of new versus practiced sequence order and RSIs of 0, 100, and 200 ms.

A planned comparison showed that with the 100 ms RSI (used also during practice) participants had faster response times with the practiced than with the new sequences. This confirmed that participants had learned the sequence, *F*(1, 22) = 96.1, $p < .001$. As the practiced sequence was faster than the new sequence also with the 0 and 200 ms RSIs, *Fs*(1, 22) > 24.3, *ps* < .001, aware and unaware participants appear to have used sequence knowledge also when RSI differed from the one used during practice.

Figure 3.3 and planned comparisons showed that practiced sequences were executed faster than new sequences by aware and unaware participants separately at 0 ms RSI, *Fs*(1, 22) > 5.4, *ps* < .05, which benefit rose as RSI increased to 100 and 200 ms RSI, *Fs*(1, 22) > 12.4, *ps* < .001. These findings are supported by a Sequence x RSI interaction, *F*(2, 44) = 14.8, $p < .001$, indicating that, across both awareness groups, the benefit was larger when RSI was longer. Also, for both aware and unaware participants the advantage of familiar over new sequences was larger in the 100/200 ms RSI than the 0 ms RSI condition, *Fs*(1, 22) > 10.9, *ps* < .01 (100 and 200 ms RSI did not differ), suggesting that the use of both implicit and explicit knowledge improves when RSI increases. For aware participants these findings are in line with the earlier study (Ter Schegget & Verwey, 2009a), but the finding that even unaware participants showed a performance increase with RSI was new.

Planned comparisons in the 100 and 200 ms RSI test conditions showed that aware participants benefited more from sequence knowledge than unaware participants, $Fs(1, 22) > 5.5$, $ps < .05$. For the RSI 0 ms condition there was a trend, $F(1, 22) = 3.5$, $p = .07$. These comparisons were supported by the Awareness x Sequence interaction, $F(1, 22) = 14.8$, $p < .001$. So, with the familiar sequence, aware participants benefited more than unaware participants from a longer RSI.

ERRORS

Throughout all 16 blocks in the present experiment, participants had a mean error percentage of 1.7%. An Awareness (3) x Block (8) ANOVA with Awareness as between subjects variable on the arcsin transformed error percentages of the practice phase did not show any significant result. An Awareness (2) x Sequence (2) x RSI (3) ANOVA on the arcsin transformed error percentages of the test phase showed that overall participants made more errors in the new sequence blocks (1.9%) than in the blocks with the familiar sequence (1.4%), $F(1, 22) = 5.1$, $p < .05$. The analysis also showed a significant effect of RSI, $F(2, 44) = 4.2$, $p < .05$. The error percentages of the RSI 0, 100, and 200 ms condition were respectively 2.0%, 1.4%, and 1.6%, suggesting that a different RSI in the test phase required adjustment. There were no significant effects of awareness on errors.

3.3.3 Discussion

The aim of the present experiment was to examine with an improved version of the serial RT task indications for the development and use of implicit and explicit sequence knowledge during and following execution of the aiming movements. This time, we used SOC sequences and shorter RSIs, than in the earlier study (Ter Schegget & Verwey, 2009a). SOC sequences prevent that participants learn a sequence because some elements or some transitions between elements occur more often than others (Shanks & St.John, 1994). We used shorter RSIs, as we were interested to find out how application of explicit knowledge develops over time. The present study also used new sequences as control sequences (instead of random ones) and an intermediate target diameter compared to the earlier study.

The results replicated our earlier study (Ter Schegget & Verwey, 2009a) in that the (more) aware participants benefited from a longer RSI, suggesting that they needed RSI to apply their explicit sequence knowledge and could not do so during execution of the preceding aiming movement. However, whereas the previous study showed that unaware participants did not benefit from a longer RSI, suggesting that their knowledge was already fully applied during execution of the preceding aiming movement, this time unaware participants benefited from a longer RSI too (though less than aware participants). There are several explanations for this difference with the earlier results.

A first explanation for unaware participants benefiting from longer RSIs with the practiced sequence is that participants in this experiment were more aware than in the previous study (for example, due to the use of a four-element SOC sequence). After all, the questionnaire distinguishes only more and less aware participants, but it can not exclude that participants with limited awareness do not have some remaining awareness. This would mean that this time the awareness questionnaire was not a proper tool for dividing the participants into different awareness level groups. A second explanation for the benefit of longer RSIs for unaware participants is that this time there were three alternatives following each response whereas there were only two real alternatives in a particular sequence in the previous study (of the five potential alternatives). Perhaps, implicit sequence knowledge involves only global information as to the direction of a movement that can be used with three alternative movements (the present experiment), but not with two alternative movements (as in the previous experiment). These two explanations may be interdependent in that more awareness may have developed in the SOC sequence of the present study.

A third explanation for the fact that in the present study implicit sequence knowledge was better used with longer RSI's is the target diameter. In the earlier study of Ter Schegget and Verwey (2009a), we used target diameters of 9 and 24 mm. The results showed that with 9 mm there is hardly any benefit of awareness, but in the case of the 24 mm target diameter there seems to be some benefit, although this is not significant. In the present study the target diameter was 16 mm. With this diameter we found a benefit for unaware participants when RSI was 0 ms. This suggests that unaware participants only benefit when the diameter is larger.

In any case, the fact that unaware participants were able to better use their sequence knowledge with longer RSIs, can not have been caused by using new sequences instead of random sequences (Ter Schegget & Verwey, 2009a), or shorter response times. That is, using a new instead of a random sequence may have affected the apparent size of the learning effect, but this can not explain that unaware participants were faster with practiced sequences as RSI increased. Furthermore, additional analyses on just sequence cycles 2-5 in each block to test the explanation that a new sequence may have been learned to some extent during each block of the test phase revealed the same effects. Also, comparison of the response times in the present and the earlier study (Ter Schegget & Verwey, 2009a), do not support that the present response times were perhaps too short to apply implicit knowledge (they amounted to 577 ms and 574 ms in the random sequences of Experiments 1 and 2 in Ter Schegget & Verwey (2009a), and 559 ms in the new sequences of the present study).

The earlier study of Ter Schegget and Verwey (2009a) showed that with an RSI of 200 ms aware participants immediately moved their hand to the next target, while unaware participants seemed to have moved their hand to the location that had the same distance to all four target areas. With the 0 ms RSI this difference between aware and unaware participants was not observed. The 100 ms RSI during practice in the present study was used to find out whether it would suffice for aware participants to immediately move to the next target before it was presented, and whether a 100 ms RSI would be sufficient to develop sequence knowledge. The distance effects we found in the present study suggest that both aware and unaware participants immediately moved their hand to the next target, which is in line with the 0 ms RSI results in the previous study (Ter Schegget and Verwey, 2009a). Apparently, a 100 ms RSI is too short for aware and unaware participants to use it to start moving to the next target and make it useful for unaware participants to first move to a central position.

Finally, the present study was carried out to see how application of explicit knowledge develops over time. The previous study of Ter Schegget and Verwey (2009a) showed no difference between the 200 and 400 ms RSIs in the test phase. This indicated that a 200 ms RSI is sufficient to use explicit sequence knowledge about the next target. The present study therefore used RSIs of 0, 100 and 200 ms. This time, the results showed no difference between the 100 and 200 ms RSIs in the test phase. So, applying (implicit and explicit) sequence knowledge seems to require less than 100 ms in the present version of the serial RT task.

In short, the aim of the present experiment was to replicate the findings of an earlier study (Ter Schegget & Verwey, 2009a). The present results confirm that applying explicit sequence knowledge improves with longer RSIs. It seems that explicit knowledge is applied already during execution of the preceding movement, but even more after the preceding movement has been completed. Moreover, a 100 ms practice RSI appeared sufficient for aware and unaware participants to move their hand immediately to the next target before it was presented, just like a 0 ms practice RSI in the previous study. Also, performance in the present study was not different for the 100 and 200 ms RSI conditions, indicating that the development of sequence knowledge is reduced only with RSIs that are less than 100 ms. However, unaware participants in the present study behaved differently than in the study of Ter Schegget and Verwey (2009a) in that they were able to better use their implicit sequence knowledge with longer RSIs (like aware participants). This may have been caused by the intermediate target diameter (16 mm), or the smaller number of target areas, or the higher number of alternative responses, or the better controlled variables and power in the present study, or some residual explicit knowledge in unaware participants.

Chapter 4

Inserting a fixed element in between choice elements of the serial reaction time task: effects on implicit and explicit learning

4.1 Abstract

Forty eight participants practiced an aiming movement version of a serial RT (reaction time) task. Half of them practiced a 12-item sequence by tapping four targets on the corners of an imaginary diamond. The other half practiced a 24-item sequence consisting of the same 12-item sequence but in which each item alternated with tapping a target in the centre of the diamond. The present experiment addressed whether the repeated hitting of the centre target interfered with the development of implicit and/or explicit sequence knowledge. Also, the experiment investigated the transfer of implicit and/or explicit sequence knowledge from the sequence as practiced (with or without centre target) to the other group's sequence (i.e. without or with centre target, respectively) condition. The results showed development of both explicit and implicit sequence learning irrespective of the presence of the centre target. Transfer to the other group's sequence was limited to participants who had practiced with a centre target. These participants appeared to use implicit sequence knowledge also when the centre target was removed. So, both implicit and explicit sequence knowledge are hardly affected by alternating sequential movements with a movement to a fixed central position. Moreover, the way in which the sequence has been practiced predicts the capacity to use both explicit and implicit sequence knowledge.

4.2 Introduction

In our everyday life we constantly carry out movement sequences. These sequences form the building blocks of tasks like playing the piano or typing, and they are also at the basis of actions such as putting on one's shoes after putting on one's jeans, or opening the door after turning the key. Many researchers are interested in investigating movement sequences and use keying sequences to study properties of sequential skills in humans. Some of these studies concentrated on effects of extended practice (e.g. Bird & Heyes, 2005; Shanks & Cameron, 2000; Verwey & Clegg, 2004), others on dual task (e.g. Curran & Keele, 1993; Heuer & Schmidtke, 1996; Jiménez & Vazquez, 2005), sequence length (e.g. Garcia-Colera & Semjen, 1988; Verwey, 2003a; Verwey & Eikelboom, 2003), or brain structures related to movement sequences (e.g. Bischoff-Grethe, Goedert, Willingham & Grafton, 2004; Boyd & Winstein, 2001; Gordon, Lee, Flament, Ugurbil & Ebner, 1998). As much research has already been carried out on sequences of a very simple movement - pressing a key - we were interested in the mechanisms underlying the development and use of explicit and implicit knowledge with series of aiming movements.

Explicit learning usually is characterized by the ability to verbally express knowledge of the movements carried out. Implicit learning on the other hand is characterized by the ability to learn something without being aware of what has been learned. Conditioning is one of the examples of implicit learning (e.g. Knight, Nguyen & Bandettini, 2003; Olsen & Fazio, 2001). Conditioning implies skill learning by repeated practice and reinforcement, so that after a while the operation of the skill becomes tacit. For instance, behavioral elements of driving gradually become more automatic and the driver is eventually unaware of all the individual actions that are executed. Implicit learning of movement sequences often has been investigated with the serial reaction time (RT) task which was introduced by Nissen and Bullemer in 1987. In the typical serial RT task, participants see four horizontally aligned target areas on a computer screen. When one of them lights up, participants press the spatially compatible key on a keyboard. After a short interval the next target lights up and the participants react by pressing another key, and so on. A sequence usually consists of 10 to 12 stimuli and then the same sequence starts again.

To our knowledge, aiming movements have only been used in three serial RT studies (Corr, 2003; Dominey, Lelekov, Ventre-Dominey & Jeannerod, 1998; Liu, Lungu, Waechter, Willingham & Ashe, 2007). Obviously, the most striking difference between pressing keys and executing aiming movements is that it takes more time and processing to hit a target with an aiming movement than to press a key. This might have repercussions for the development and use of implicit and explicit knowledge. In an earlier study (Ter Schegget & Verwey, 2009a) participants responded in a serial RT task to the onset of six target areas located equidistantly on an imaginary circle. We found indications that the development of implicit and explicit sequence knowledge is not disturbed by using aiming movements as sequence elements, but that in contrast to implicit knowledge, explicit knowledge is applied only after the preceding aiming movement has been completed. However, in a subsequent study (Ter Schegget and Verwey, 2009b), we found that both implicit and explicit knowledge can not be applied during execution of the preceding aiming movement.

In the present study, we examined how development and use of implicit and explicit sequential skill is affected by tapping one specific target at the centre of the serial RT targets, every time a normal sequence target has been hit. The rationale is that RTs in Ter Schegget and Verwey (2009a) suggested that participants without awareness moved their hand to the centre of the imaginary circle on which the targets were positioned in order to quickly reach each next target, whereas participants with awareness went straight to the next target. As sequence learning was found also with participants without awareness this might imply that the development and expression of implicit sequence knowledge is not affected by moving the hand to some fixed, central position.

There is reason to believe that implicit, more than explicit, sequence knowledge may be affected by alternating sequential movements with a movement to a fixed central position. The literature shows two types of serial RT studies that may be relevant to the question how repeated execution of a fixed movement might affect sequence learning in the serial RT task. First, some studies used an alternating serial reaction time (ASRT) task (e.g. Feeney, Howard & Howard, 2002; Howard & Howard, 1997; Howard, Howard, Japikse & Eden, 2006). In this task every element of a sequence is followed by a random element. For instance, the sequence 124132342143 in a serial RT task would become 1r2r4r1r3r2r3r4r2r1r4r3r (with "r" standing for a random trial). The ASRT task is used to examine the development and expression of just implicit sequence knowledge as in this task awareness appears not to develop. If inserting a single response in between elements of a sequence is comparable to inserting random elements like in the ASRT task, hitting a central target will slow development of implicit sequence knowledge and prevent development of explicit sequence knowledge.

A second relevant serial RT task is the version in which tones are presented in between successive actions. Counting these tones, which requires attention but is an action that can be separated easily from the sequencing task, appears to reduce especially implicit sequence learning (e.g. Heuer & Schmidtke, 1996; Nissen & Bullemer, 1987; Stadler, 1992, 1995). So, these two related types of studies do not allow clear indications what to expect when a central target is to be tapped.

Keele, Ivry, Mayr, Hazeltine and Heuer (2003) asserted that sequence learning is based on two neurocognitive learning systems. The first is a multidimensional learning system that builds associations between events irrespective of whether they are in the same or in different dimensions. This system requires attention, is responsible for awareness, and learning can be implicit or explicit. The flexibility of this system might allow it to ignore hitting the centre target, as it obviously is a conspicuous element of the sequence (cf. Sternberg, Knoll & Turock, 1990). Consequently the contribution of this system to sequence learning and expression which is largely explicit may not be affected by repeatedly hitting the centre target. Keele et al. (2003) postulate also a series of unidimensional systems that do not require attention and that are responsible for implicit sequence learning. Given that these unimodal systems are associative and may require successive elements to be simultaneously active in working memory (Frensch & Miner, 1994), their contribution to implicit learning may indeed be interfered with by hitting the central target. So, the Keele et al. model seems in line with the notion that inserting a fixed element in between successive sequence elements will reduce development and expression of implicit knowledge more than of explicit knowledge.

In the present study we had half of our participants (the *no-centre practice group*) practice the aiming movements of a 12 element serial RT task with four targets in the form of an imaginary diamond shape. The remaining participants (the *centre practice group*) practiced the same 12 element sequence, but tapped a target in the centre of the diamond in between each sequence target, essentially turning the sequence into a 24 element sequence. We examined to what extent performance and awareness were influenced by hitting the same target in between the sequential targets. Subsequently, all participants performed in the same test phase. In this phase, two blocks involved the practiced and two a new sequence. One of each pair of blocks involved hitting the centre target in between each sequence element whereas the other block did not. This test phase allowed us to examine whether introducing (for the no-centre practice group) or removing (for the centre practice group) the centre target affects the performance differently for participants with and without awareness.

4.3 Experiment

4.3.1 Method

PARTICIPANTS

In exchange for course credits, 48 first-year students of the University of Twente participated in the present experiment. None of the participants had prior experience with a sequence learning experiment and none was informed about the actual purpose of the study. All participants were right-handed, had normal or corrected to normal vision, and signed informed consent forms before the experiment started.

TASK

Four white circles with a diameter of 32 mm were continuously presented on the black background of a touch sensitive screen. Together these target areas formed an imaginary diamond with four sides of equal length. The centre of all four target areas was at 6.5 cm from the centre of the diamond. In some conditions, an equally sized fifth target area was presented in the middle of the imaginary diamond (see Figure 4.1). When a red ring was displayed on top of one of the white target areas (inner white circle diameter 12 mm), participants were to hit the white inner part of that target area as fast as possible with a special stylus. Immediately after they had done so, the red ring was removed and was displayed on top of another target area that was to be hit next. The response to stimulus interval, RSI, was 0 ms.

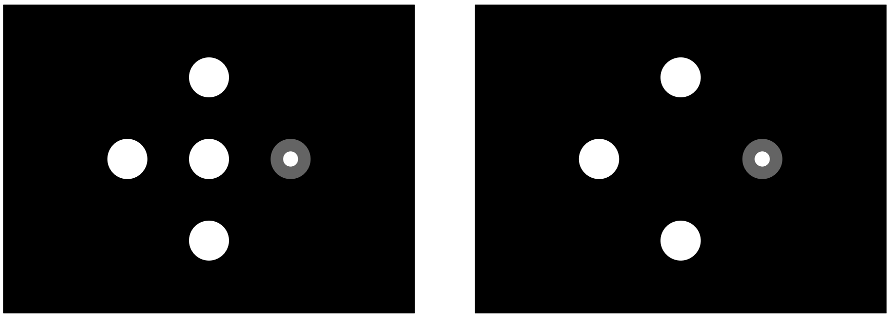

Figure 4.1: An example of the touch screen appearance of the centre (left panel) and the no-centre (right panel) practice groups. Participants in the centre practice group always tapped the middle circle after hitting one of the circles on the diamond shape. In both conditions the white inner part of the target area was to be hit.

Participants were randomly assigned to one of two practice groups. The no-centre practice group practiced with the above mentioned four target areas while the centre practice group practiced with a fifth target area at the centre of the other four target areas. Every time participants in the centre practice group had hit a target on the diamond shape correctly, the centre circle turned into target. Consequently, for the no-centre practice group every odd element in the sequence involved hitting one of the four outside targets and every even element involved hitting the centre target.

Both experimental groups were told to hit the white part of the target areas that lit up, but were not informed about the repeating pattern in which the targets appeared. The actual sequence consisted of a 12 element second-order conditional (SOC), which implies that an element can be predicted only when taking the two preceding targets into account (Schvaneveldt & Gomez, 1998). This type of sequence cannot be learned on the basis of the relative frequency of the sequence elements or of the transitions between successive elements because each element and each transition appears equally often. The base sequence we used was 124132342143. To avoid effects of the hand covering the right or lower target, three further versions of the base sequence were derived by rotating the base pattern each time 90 degrees (thus yielding 231243413214, 342314124321, and 413421231432). Equal numbers of participants in each group practiced one of these four sequences.

Participants in the centre practice group practiced with the centre target inserted between successive elements, yielding 152545153525354525154535 as base sequence (with “5” representing the centre circle).

PROCEDURE

After signing the consent form, participants received instructions about the experiment on the screen, extended with oral information. In total, the experiment involved 14 blocks of nine sequence repetitions (yielding 9 x 12 = 108 taps in each no-centre block and 9 x 24 = 216 taps for each centre block). Participants started with a practice phase of nine blocks. Half of the participants practiced with and the other half without the centre target. The first block contained another SOC sequence than the one in the next eight blocks and was meant to help participants getting familiar with the experimental setting and the stylus.

The practice phase involved the base sequence (with or without the centre target) for a fourth of the participants and each of its rotated versions was distributed across the remaining participants. The practice phase was followed by the test phase consisting of four blocks in balanced order. Two test blocks contained the two practiced versions of the practice phase. One of these excluded the centre target and the other included it. The other two blocks of the test phase involved a new sequence, again one block with and one block without centre target. For a particular participant, these two new SOC sequences were different from sequences used before in the practice phase (i.e. Blocks 2-9), but contained the same characteristics (for example, always one reversal, like 323). Sequences were counterbalanced across participants. The 14th and last block of the experiment again contained the familiar sequence of the practice phase. After the last block, participants filled out an awareness questionnaire about the sequence order.

The paper awareness questionnaire was used to divide the participants in three different awareness groups. It contained four parts and each part was on another sheet of paper like in the previous studies. Part A asked the participants to choose the best formulation about the order in which the stimuli appeared: whether (1) the order was random; (2) some positions occurred more frequently than other positions; (3) their hand tended to go in a certain direction; (4) the order was often predictable; (5) the same order occurred more than once; or (6) the same order occurred throughout the whole experiment. In part B, the *free recall* part, participants were informed that the experiment had involved a sequence with a fixed order. They were asked to draw this order or parts of it, by using arrows and numbers, in a figure already containing the targets. An example was drawn on the same page. Part C, the first *recognition* part, showed 24 pictures in which a possible order was drawn of 4 (12 pictures), 6 (8 pictures) or 12 (4 pictures) sequence positions. For each picture, participants wrote down whether they had executed the shown order and, on a scale of zero (uncertain) to 100 (certain), how sure they were about this. Part D of the questionnaire comprised *forced recognition*. It showed four pictures with the (four) alternative practiced sequences. Participants were told they had executed one of those four and were to select the correct one. Again, certainty also was to be filled in on a scale from zero to 100. All participants filled out the questionnaire parts in the same order. Once questions on a sheet of paper had been filled out, participants were not allowed to look back, or make changes.

APPARATUS

The targets were displayed and tapped on a 17 inch IIYAMA Vision Master MF8617E monitor producing a 640 x 480 pixel VGA image, with a ClearTek capacitive touch-sensitive layer that senses the location of a tap with a resolution of 1024 x 1024 pixels. The taps were carried out with a special stylus. Due to system delays RSI varied between about 9 and 27 ms, which delay was not notable. The touch sensitive screen was mounted in a hole in a table, so that the screen surface had an angle of about 30° with the table surface. The stimulus representation and data collection were controlled by a 333 MHz Pentium-based PC that was connected to the touch screen monitor, and used Micro Experimental Laboratory (MEL version 2.0) software to control the experiment. The experimenter was sitting behind a second computer screen that was attached to the Pentium-based PC and watched the participants executing the experiment. The participants were sitting behind the touch sensitive display with their head in a chin and forehead rest, to ensure a constant viewing distance of 45 cm between the eyes and the monitor surface.

DATA ANALYSIS

In the present study, we define response time as the time between target onset and hitting that target. Due to technical limitations we did not distinguish between reaction time (from target onset to releasing the previous target area) and movement time (from releasing the previous target to hitting the current target). The first two trials of a block, errors and the two trials following an error were excluded from the analyses. Also, the trials with a response time that was longer than three times the standard deviation from the average response time in a block across participants within a group (centre or no centre practice group) were excluded from the analyses. The latter removed about 2% of the data.

4.3.2 Results

AWARENESS GROUPS

On basis of part D of the paper awareness questionnaire, in which participants were to recognize their practiced sequence out of four alternatives, participants were divided into two groups, regardless of whether they had practiced with the centre target or not. As it turned out, exactly half of the participants recognized the sequence they had practiced, and the other half had not, yielding two groups of 24 participants. Within these two groups, participants were rank ordered according to the number of correct transitions they had produced by free recall in part B of the questionnaire. If participants had the same ranking, the number of correctly recognized parts of the practiced sequence (Part C) and, if necessary their certainty scores (Part C and D), were used to order them any way. The 16 participants with the most correct transitions were classified as aware, and the 16 participants with the least correct transitions were classified as unaware. The remaining 16 participants were classified as partially aware. Table 4.1 shows the details of each of the three groups. Remarkably, both the centre and the no-centre practice groups contained the same number of participants in all three awareness groups. This demonstrates that the requirement to hit the centre target had not affected the development of explicit knowledge.

Table 4.1: Characteristics of the three awareness groups according to the questionnaire results and the numbers of participants in each group.

Awareness group	Participants selecting the correct statement in questionnaire (Part A)	Mean number of correct transitions (12 max.) (Part A)	Median certainty of identifying the correct sequence (scale 0 - 100) (Part C/D)	Median certainty of identifying the incorrect sequences (scale 0 - 100) (Part C/D)	Participants in centre practice group (*n* = 24)	Participants in no-centre practice group (*n* = 24)
unaware (*n* = 16)	*n* = 2 (13%)	1.19 (range 0 - 3)	25.0	23.5	*n* = 8 (33%)	*n* = 8 (33%)
partially aware (*n* = 16)	*n* = 7 (44%)	2.19 (range 0 - 6)	40.0	46.5	*n* = 8 (33%)	*n* = 8 (33%)
aware (*n* = 16)	*n* = 12 (75%)	4.81 (range 3 - 7)	64.5	71.5	*n* = 8 (33%)	*n* = 8 (33%)

In part A of the awareness questionnaire participants marked out of six the best formulation for the order in which the stimuli had appeared. As can be seen in Table 4.1 the results of part A of the questionnaire support the division into the three awareness groups: 12 of the 16 aware participants had checked the right formulation compared with only two out of 16 unaware participants, $\chi^2(1) = 5.2$, $p < .05$. To find out whether the three awareness groups were different according to their certainty scores, a Kruskal-Wallis ANOVA was conducted on rank orders for certainty of accepting the executed sequence or rejecting the alternative sequences (parts C and D of the questionnaire). The results showed that median certainty rating increased with ranked awareness, for executed sequence $H(2, n = 48) = 11.3$, $p < .01$, and for incorrect sequences $H(2, n = 48) = 11.2$, $p < .01$.

PRACTICE PHASE

Beforehand it was not clear whether the experimental effects in the target group would appear in the movement to the centre target, away from the centre target, or the sum of both movements. However, separate analyses on response times of these three possibilities showed that test phase effects were strongest with the movement away from the centre target, whereas in the practice phase there was no difference in effect sizes between the three possibilities. Therefore, all analyses reported below were conducted on the movement away from the centre target.

Figure 4.2 depicts the response times of the three awareness groups in the practice phase for the no-centre and centre practice groups. A Group (2: no-centre vs. centre practice group) x Awareness (3: aware, partially aware, unaware) x Block (8: block 2-9) ANOVA with Block as repeated measure was carried out on the response times obtained in the eight practice blocks. The main effects showed that performance improved during practice, $F(7, 294) > 31.4$, $p < .001$, and that awareness was associated with a higher execution rate, $F(2, 42) = 4.1$, $p < .05$. Figure 4.2 shows that in the no-centre practice group awareness is associated with faster responding while in the centre practice group the partially aware group was faster than the aware group. This is supported by planned comparisons: In the no-centre practice group only the difference between aware and unaware, and in the centre practice group only the difference between partially aware and unaware participants reached statistical significance, $Fs(1, 42) > 3.6$, $ps < .05$. As these differences were available already in Block 1 with the different sequence as well, they can be attributed to group differences. When comparing Block 2 with Block 9 (Block 1 had another sequence) both the centre and no-centre practice group showed significant improvement, $Fs(1, 42) > 10.7$, $ps < .01$. A planned comparison showed that this improvement was higher for the no-centre than the centre practice group, $F(1, 42) = 12.4$, $p = .001$. However, planned comparisons demonstrated that within both practice groups this improvement was not significantly different for aware compared with unaware participants, $Fs(1, 42) > .18$, $ps > .20$. So, in both practice groups aware and unaware participants learned the sequence to the same degree, and this was the case irrespective of tapping a centre target.

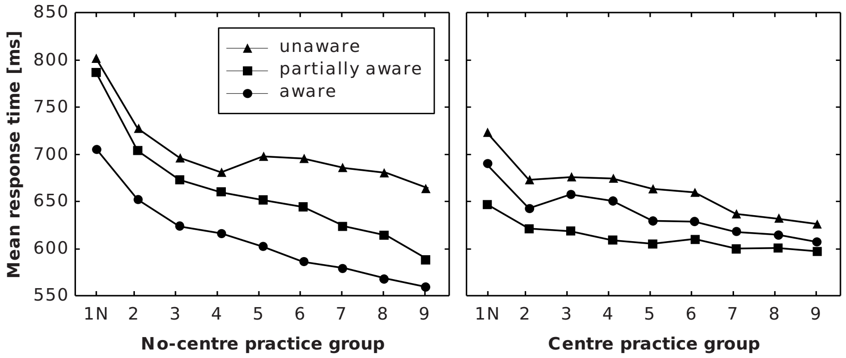

Figure 4.2: Mean response times of the three awareness groups in the nine practice blocks. The first block contained a different sequence order (N) than the other eight blocks. The left panel shows the mean response times for the no-centre practice group. The lines in the right panel show the mean response times of the movement away from the centre target of the centre practice group.

TEST PHASE

Familiar condition

A Group (2: no-centre vs. centre practice group) x Awareness (2: aware vs. unaware) x Centre (2: with vs. without centre circle) x Sequence (2: new vs. practiced) ANOVA with Centre and Sequence as repeated measure, was carried out on the response times. The partially aware group was excluded, because our interest focused on the difference between aware and unaware participants. Figure 4.3 shows the mean response times of the two awareness groups in each practice group.

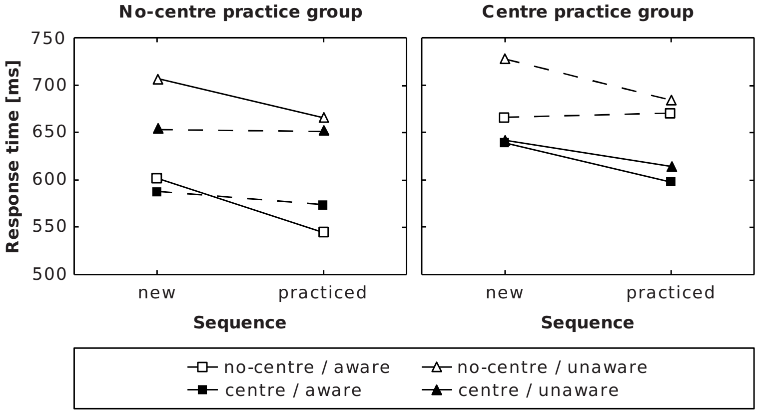

Figure 4.3: Mean response times of the aware and unaware participants for both the no-centre (left panel) and centre practice group (right panel) in the test phase. The solid lines show the results of the practice groups in their own practice condition. In the blocks with a centre target the response times involve the movement away from the centre target.

Planned comparisons showed that in the test phase the practiced sequence was carried out faster than the new sequence for both practice groups in their familiar centre target condition, *Fs*(1, 28) > 19.2, *ps* < .001 (solid lines in both panels), confirming the practice effect of both groups observed in the practice phase. When analyzing aware and unaware participants separately, this appeared to hold for both aware and unaware participants, *Fs*(1, 28) > 6.7, *ps* < .01. This seems to confirm the conclusion from the practice phase that both implicit and explicit sequence knowledge were not only acquired, but were applied also irrespective of whether there was a centre target. However, the difference between aware and unaware participants across practice and new sequences was considerably larger in the no-centre than in the centre practice group, *F*(1, 28) = 6.3, *p* = .01, and this awareness effect was in fact only significant in the no-centre practice group, *F*(1, 28) = 12.5, *p* = .001. So, the centre target seems to reduce the expression of explicit sequence knowledge (as demonstrated in the awareness test) in the centre practice group. Another possibility would be that explicit sequence knowledge was not used in the centre practice group and the effects in this group are caused by implicit sequence knowledge.

In short, the analyses of the condition participants had been practicing in, show that both aware and unaware participants were faster on the practiced than on the new sequence. In addition, only in the centre practice group the difference between aware and unaware participants disappears. It seems that explicit sequence knowledge does not have a surplus value compared with implicit sequence knowledge (with an RSI of 0 ms). So, there were some general group differences between the centre and no-centre practice groups.

Unfamiliar condition

To find out whether participants used their sequence knowledge in the condition they had not been practicing in, separate planned comparisons were executed for the two practice groups. In the no-centre practice group the Centre x Sequence interaction was significant for both aware and unaware participants, $Fs(1, 28) > 5.2$, $ps < .05$, indicating that (aware and unaware) participants benefited more from their sequence knowledge in the (familiar) no-centre than in the (unfamiliar) centre condition. In contrast to the suggestion by the dashed lines in the left panel of Figure 4.3, aware participants were not significantly faster than unaware participants, $F(1, 28) < 1.9$, $p > .18$. This indicates that including a centre target prevented use of implicit and explicit sequence knowledge that had developed without centre target.

In the centre practice group the Centre x Sequence interaction was significant for only the aware participants, $F(1, 28) = 7.1$, $p < .01$, but not for the unaware participants: $p > .20$. This difference was supported by an Awareness x Centre x Sequence interaction for an ANOVA on just the centre practice group, $F(1, 28) = 5.6$, $p < .05$. Unaware participants had faster response times for the practiced than the new sequence in the conditions without a centre target, $F(1, 28) = 7.3$, $p < .01$, while aware participants did not, $F(1, 28) < 1$, $p > .20$. Apparently, when the centre target is removed unaware participants are able to still apply their sequence knowledge, while aware participants are unable to continue using their sequence knowledge after removing the need to hit the centre target.

The possibility that awareness would be associated with a better general (sequence independent) movement skill was not borne out. A separate Awareness (3) x Block (3) ANOVA for the two pattern groups was executed on the response times of Block 1 (of the practice phase) and the block in the test phase that involved a different but new sequence. The results did not show a difference between the awareness groups in the new blocks for both groups, *Fs*(2, 21) < 1, *ps* > .20.

In conclusion, the results of the test phase showed that only unaware participants in the centre practice group were able to transfer their sequence knowledge to the condition without centre target.

ERRORS

A Block (8) x Awareness (3) x Group (2) ANOVA was carried out on the arcsin transformed error percentages in the eight blocks of the practice phase. In the centre practice group the centre target was included, as participants did make errors with this target too. The analysis showed that participants in the centre practice group made fewer errors (4.4%) than participants in the no-centre practice group (5.9%), *F*(1, 42) = 6.3, *p* < .05, and that all participants improved during practice (from 6.7% to 4.3%), *F*(7, 294) = 3.7, *p* < .001.

The error percentages of the four blocks of the test phase were analyzed with an Awareness (3) x Group (2) x Sequence (2: random vs. fixed) x Centre (2: with centre vs. no centre) ANOVA. Again, the centre target was included in the analysis, as participants did make errors with this target. As in the practice phase, it showed that participants in the centre practice group made fewer errors (4.3%) than participants in the no-centre practice group (6.2%), *F*(1, 42) = 8.7, *p* < .01 Besides, the analysis showed that participants made fewer errors in the two blocks with a centre circle (5.0%) than the two blocks without a centre circle (5.5%), *F*(1, 42) = 4.5, *p* < .05. There was an effect of performing in the unfamiliar condition for only the centre practice group, *F*(1, 42) = 6.7, *p* < .05: participants of this group made more errors in the condition without the centre target (4.8%) than in the condition with the centre target (3.9%). There was no effect of awareness on errors in both phases.

4.3.3 Discussion

The present study used the serial RT task (Nissen & Bullemer, 1987) to investigate implicit learning of aiming movements with and without a repeating centre target. Half of the participants practiced a 12-item sequence, the other participants practiced the same sequence, but with the repeating centre target. This changed the

12-item sequence into a 24-item sequence, in which every even stimulus was the repeating centre stimulus. First of all, there were as many aware and unaware participants in both groups, irrespective of whether there was a centre target or not. In terms of the model of Keele et al. (2003) this confirms our expectation that the multidimensional system can filter out the taps at the centre target.

In the practice phase we examined whether performance and awareness are influenced by tapping the centre target. First of all, the results showed that explicit knowledge developed as usual, irrespective of the centre target. The results also showed that within both centre groups there was significant improvement. More specifically, the results showed that aware and unaware participants in both pattern groups had learned the sequence, and that the faster response times of aware participants were not caused by a generally better (sequence unspecific) movement skill. Apparently, the movement to the next target can be prepared already during the preceding movement(s).

The practice effects were small. This may be a consequence of the RSI of 0 ms that was used in the present experiment: Participants were probably unable to fully benefit from their preparation or did not prepare. Overall, in the practice phase the repeating centre stimulus did influence performance and awareness in some way: although both practice groups demonstrated that the movement to the next target can be prepared during the preceding movement(s), practice effects were smaller for participants that practiced with the repeating centre stimulus. A possible cause for this might be that in the centre group explicit knowledge is not used as much as in the no-centre group. Moreover, within both practice groups the development of implicit and explicit sequence knowledge was the same.

In the test phase we investigated whether a fixed movement element that separates the elements of a sequence of aiming movements in a serial RT task influences the expression of implicit and explicit sequence knowledge. This was done, because in an earlier study it seemed as if aware participants had moved their hand from target to target, while unaware participants moved their hand to a strategic (centre) point that had the same distance to all target areas (Ter Schegget & Verwey, 2009a), suggesting that the fixed movement does not interfere with implicit knowledge. For the present study we would therefore predict a disturbance of explicit sequence knowledge by the centre target, as aware participants are not used to move their hand to a strategic (centre) point, and there was no performance reduction for unaware participants.

The results of the test phase showed that when participants performed in their own (familiar) practice condition, the centre target seemed to reduce the expression of explicit sequence knowledge. This is what we expected based on our earlier study (Ter Schegget & Verwey, 2009a), because in that study aware participants immediately moved their hand to the next target after touching the preceding target right. The results in the test phase showed also that only unaware participants in the centre practice group were able to transfer their sequence knowledge to the unfamiliar condition. A possible explanation for this awareness difference when the centre target was removed is that aware participants had to inhibit the inclination to move to the centre target, and this suppression was unnecessary for unaware participants who were still able to use their sequence knowledge. The inclusion of the centre target forced participants in the no-centre practice group to make an extra move in between the sequence elements. This new movement had to be paid attention to and probably obstructed participants to use their sequence knowledge. In short, including a centre target does not change performance of both unaware and aware participants, and removing a centre target hampers performance of only aware participants. It seems that the multidimensional system (Keele et al., 2003) learns despite the centre target, but this can not be used when the centre target is removed or introduced.

Table 4.1 shows that in the present experiment even the most aware participants could produce only seven stimulus pairs out of twelve by free recall in Part B of the questionnaire. This may be a consequence of the 0 ms RSI that was used in the present study. Key pressing studies with an RSI of 0 ms showed better awareness with longer RSIs (Destrebecqz & Cleeremans, 2001, 2003). Another explanation is that participants may recognize the sequence order on the basis of some conspicuous sequence fragments at the recognition part of the questionnaire, while their explicit knowledge of the entire sequence is limited (and the score on the free recall part of the questionnaire maximal seven stimulus pairs). A third explanation holds only for the centre practice group and states that explicit knowledge is difficult to express, as the centre target may impede the forming of associations. The awareness questionnaire is used to create a clear distinction between the three awareness levels of the different participants: unaware, partially aware and aware. Table 4.1 does demonstrate that on all parts of the questionnaire this distinction is apparent. For example, 75% of the aware participants made a correct choice on element order out of the six formulations in part A compared to only 13% of the unaware participants. So, the separation of participants in different awareness groups seems to be a proper distinction of qualitatively different knowledge.

In conclusion, both implicit and explicit sequence learning developed with a fixed element in between each of the elements of a sequence of aiming movements. The results of the test phase showed that aware participants were unable to transfer their sequence knowledge when the centre target was included or excluded. Only unaware participants in the centre practice group were not affected by removing the centre target. This is reasonable, as this is the one condition in which there was not really a transfer as unaware participants probably moved their hand to the central position when practising the sequence. So, the application of both explicit and implicit sequence knowledge is closely connected to the way in which the sequence had been practiced. Moreover, it seems that explicit sequence knowledge was not used in terms of movements but in terms of spatial coordinates because it is most convenient to ignore the centre target. On the contrary, implicit sequence knowledge was used for the execution of movements.

Chapter 5

The effect of target size and movement distance on sequence learning in an aiming movement version of the serial reaction time task.

5.1 Abstract

Schema theory and hierarchical models of motor skill have not considered indications that skilled motor behaviour may be based on various underlying representations that may be active at the same time, as suggested by models of the serial reaction time (RT) task. To examine the contribution of explicit and implicit sequence knowledge to a sequential movement skill we developed a serial RT task allowing tests typical for examining schema theory. That is, participants repeatedly cycled through a sequence of twelve aiming movements by responding to successive onsets of target areas on a touch sensitive screen. The index of difficulty (Fitts, 1954) was identical for all participants, but half the participants had small targets and short distances between the different target areas whereas for the other participants targets and distances were larger. In the test phase, target size and distances were independently manipulated. We investigated whether participants were able to transfer their implicit or explicit sequence knowledge to a condition in which the index of difficulty was the same, larger or smaller. The results showed that the notion that movement patterns are represented in a relative code, as suggested by schema theory, is largely supported in a serial RT task with aiming movements. Only when movements were more precise, transfer for unaware participants was limited.

5.2 Introduction

According to the classic schema theory (Schmidt, 1975) the execution of a motor skill involves selection of a general schema, or general motor program (GMP), that is defined in terms of the relative properties spatial layout, timing, and force.

Subsequently, the general motor program is adjusted to the task at hand by specifying parameters such as overall size of the movement pattern, overall movement time, and overall force (for a recent overview, see Shea & Wulf, 2005). Schema theory assumes it does not matter for performance whether the absolute spatial layout of target locations changes, as long as the relative spatial layout remains the same. So, schema theory assumes a general representation, the GMP, which controls the order of the individual movements. This model explains why people are able to store so many different movement skills and are capable to skilfully produce movements they have never produced before, such as when one writes on a blackboard for the first time (arm movements) after writing has been learned on paper (wrist and finger movements).

More recent research using the serial RT task has indicated that movement order may not be based on a single representation but may involve independent visual-spatial and movement based codings (Keele, Ivry, Mayr, Hazeltine & Heuer, 2003). The serial RT task involves repeatedly cycling through a series of (usually 12) responses to the onset of successive stimuli (e.g. Nissen & Bullemer, 1987). The typical finding is that while a number of participants is able to later tell (or indicate otherwise) that there was a fixed order and in which order the stimuli were presented, others are not able to indicate there was an order at all. Still, response times of all participants reduce with practice. Those who were able to verbally express the order of the sequence are said to have *explicit knowledge*, while those who were not able to do so are said to have *implicit knowledge*. These seem mere endpoints on a continuum in that many participants have explicit sequence knowledge of fragments (e.g., Cleeremans, 1994; Zirngibl & Koch, 2002). In line with the central assumption of schema theory, research with the serial RT task has repeatedly shown that spatial representations are a major feature of the sequence knowledge that is obtained (e.g., Koch & Hoffmann, 2000b). This raises the question whether the implicit and explicit representations assumed to underlie sequencing skill may be stored in a relative spatial format that can be adjusted for a particular size, just as assumed by schema theory.

Two studies show that changing the nature of the individual elements in a sequence (like when amplitudes of individual sequence elements are being changed) may reduce performance. That is, when a keying sequence had been practiced there was limited transfer to the same sequence when the elements consisted of aiming movements, whereas participants who had practiced with aiming movements were fully able to use their knowledge of the sequence to execute the sequence with key presses (Whitacre & Shea, 2000; Wilde & Shea, 2006). This asymmetric transfer was explained by the notion that executing a sequence of aiming movements requires experience with the dynamics of the individual movements; while due to the simplicity of key presses keying sequences do not. This can not be explained by schema theory. Yet, these findings are in line with models assuming hierarchically independent levels for controlling complex movement patterns and the individual elements making up the movement pattern (e.g., Sternberg, Knoll & Turock, 1990) in that higher level sequence control may be hindered when low level control (i.e., of each movement) has to take new constraints into account.

We were interested whether sequencing skill in the serial RT task is stored in a relative spatial format in participants relying primarily on implicit and those relying on explicit sequence knowledge. To that end, we had participants practice a spatial target hitting version of the serial RT task. Schema theory predicts full transfer to smaller and larger movement patterns as long as relative movements and target sizes do not change. Yet, hierarchical models acknowledge that changing the dynamics of the individual movements may hinder high level sequence control and therewith allow for reduced transfer to movement patterns with a different absolute size (even when equal in a relative sense). These models are underlined by the finding of Braden, Panzer & Shea (2008) that response time in a sequential arm movement task is influenced by the complexity of movements. To test these opposing predictions, participants in the present study executed a task in which the individual movements involved sequentially tapping with a stylus one of four targets distributed spatially on a touch screen. Half of the participants, the *small pattern group*, cycled during practice through a sequence of 12 elements with small (14 mm diameter) targets and short distances (largest distance between targets 80 mm; *14/80 condition*). The remaining participants, making up the *large pattern group*, cycled through the same sequence but with large (21 mm) targets and large target distances (120 mm; *21/120 condition*). The sequence was identical for both groups as was the Index of Difficulty of the aiming movements (or ID, Fitts, 1954). Therefore, movement times were expected to be the same too (though exceptions to Fitts' law have recently been reported for multi-element displays such as ours by Adam, Mol, Pratt & Fischer, 2006).

Following practice, participants of the small and large pattern groups executed their sequence in the other group's conditions, that is, with the same ID but with changed absolute target distances and sizes. In addition, to investigate transfer to different ID situations, the participants performed in two conditions in which only target size or target distance was changed (i.e., in a *14/120* and a *21/80 condition*). This allowed assessing whether ID is critical in transfer to differently sized movement patterns and hence whether movement complexity affects higher level sequence control. So, the experiment was aimed at testing the notion that sequence knowledge in the serial RT task involves relative spatial knowledge that can be specified with a general size parameter too, as asserted by schema theory. Furthermore, the data should indicate whether this is different for participants with little and those with full awareness, and thus whether implicit and explicit sequence knowledge both include relative spatial sequence knowledge that can be easily parameterized.

In short, our starting point was the study of Braden et al. (2008) in which the task required participants to move a horizontal lever to sequentially projected targets. They found that response time is influenced by the complexity of movements. This means that with the same ID, response times might be different as a consequence of the complexity of movements. We therefore expected longer response times for the small than for the large pattern group in the same ID conditions of the practice and the test phases. That is, the aiming movements of the small pattern group are more complex, and therefore slower, because it is more difficult to hit the smaller diameter. This would contradict Fitts' law which, however, was developed for simple repetitive movements. In addition, the hierarchical models also predict that response times may change in the test conditions with different IDs, whereas such a change is not predicted by the schema theory. Especially interesting was whether these predictions would hold for aware and unaware participants. This might namely indicate that implicit and explicit knowledge are both defined in relative spatial coordinates.

5.3 Experiment

5.3.1 Method

PARTICIPANTS

A total of 48 participants (16 men and 32 women) were involved in this experiment. All of them were right-handed undergraduate students, who reported normal or corrected to normal vision, and gave informed consent before the experiment started. They received course credits or payment for their participation. None of them had previous experience with a sequence learning experiment. The participants were randomly assigned to one of the two experimental conditions.

TASK

Participants were confronted with four white round target areas on the black background of a touch sensitive screen in the shape of an imaginary diamond with equally sized sides and diagonals. During the practice phase, the small pattern group had target areas with a diameter of 24 mm at a distance of 40 mm to the centre of the imaginary diamond (Figure 5.1). The large pattern group had target areas with a 36 mm diameter at 60 mm from the centre of the diamond. Each of the target areas turned into a target by presentation of a red ring with the same outer diameter on top of the round area. This left white round targets with either a 14 mm or a 21 mm diameter in the centre of the target for the small and large pattern groups to hit, respectively. The associated diagonal distances were 80 and 120 mm, and therefore these practice conditions were called the *14/80* and *21/120 conditions*. For these movement distances and target sizes the Indexes of Difficulty ($ID = \log_2[2 \times Distance/Target\ Size]$ - Fitts, 1954) were the same for both pattern groups, namely 3.01 for adjacent and 3.51 for diagonal targets.

Figure 5.1: The small and large target patterns used during the practice phase by respectively the small and the large pattern groups.

Participants were instructed to respond to onset of the target as fast and accurately as possible by hitting the target area (the inner white round area) with a special touch stylus that was held in the right hand. After having hit the target area the entire target turned back into a white round target area again, and the ring was presented on one of the other white round target areas. The response to stimulus interval (RSI), the time between hitting the target and onset of the next target, was 0 ms.

The sequence used in the practice and test phases consisted of 12-item second-order conditional (SOC) sequences (Reed & Johnson, 1994; Schvaneveldt & Gomez, 1998). These sequences consist entirely of so-called second-order transitions, meaning that two items are always necessary to predict the location of the next target. For instance, in the basic practice phase sequence 124132342143 the transition "12" is always followed by item "4", and item "2" alone is not predictive. This implies that RT reduction in the course of practice can not be based on learning just the frequencies of individual elements or element pairs. All sequences that we used in the present study had the same SOC structure.

As the right and lower target areas were repeatedly occluded by the right hand (participants were all right-handed), the practiced sequence involved for different participants each of the four versions of the sequence by rotation (e.g. for the above sequence these are 231243413214, 342314124321, and 413421231432). This assured that across participants the effect of occlusion was distributed evenly over sequence locations. The five other sequences, one in the first block and four in the test phase, were counterbalanced across participants. For example, Participant 1 practiced a particular sequence in Block 1, and for other participants this sequence was performed in one of the four test blocks. Among these sequences were no rotated versions of each other.

PROCEDURE

Participants were tested individually in a dimly illuminated cubicle in the psychological laboratory of the University of Twente. Before the experiment started, participants gave informed consent. They then received written and oral instructions about their task. To counteract the development of explicit knowledge, no mentioning was made of the sequential order in the experiment. Participants were asked to perform as fast as possible, but to avoid making more than 10% errors in each block. Participants then started to execute one block of 108 taps (i.e., nine repetitions of a 12-item sequence). The first block involved another sequence than the other eight practice blocks to reduce awareness. To keep accuracy high, every time participants made an error they were 'punished' with a waiting time of 1500 ms. Immediately after tapping the last target of a block, mean response time and percentage errors were displayed on the screen.

Blocks 10-17 made up the test condition which started right after completing the practice phase. This test condition included 4 blocks with a new sequence and 4 blocks with the familiar sequence. Again, each block consisted of 108 trials and, hence, of nine sequence repetitions. The test phase was identical for the small and large pattern groups, and the order of the eight test blocks was counterbalanced across the 48 participants. The distance between the target areas and the diameters of the target areas were independently manipulated between blocks, yielding four conditions, two of which with the same ID (see Table 5.1). The test phase consisted for both participant groups of the two practiced distance/target combinations 14/80 and 21/120 (each used before within one group) and of two new combinations 14/120 and 21/80 (new to all participants). Each of these conditions was performed twice: one block contained the practiced sequence and the other block a new sequence. The new sequence differed and was counterbalanced across participants. The final block of the present experiment, Block 18, was equal to Blocks 2-9 in the practice phase.

When participants finished the final block they were asked to fill out a paper questionnaire. This questionnaire was divided into four parts. It was not allowed to go back to previous parts or to correct earlier answers. Part A asked to choose the single best description about the order in which the targets appeared: (1) the order was random; (2) some positions occurred more frequently than other positions; (3) my hand tended to go a certain direction; (4) the order was often predictable; (5) the same order occurred more than once; (6) the same order occurred throughout the whole experiment.

Table 5.1: Indexes of Difficulty (IDs) in the four test conditions for the movements between adjacent and diagonal targets. The small pattern group had practiced with a small diameter and a short distance (14/80), and the large pattern group with a large diameter and a long distance (21/120) (indicated by bold type faces).

	Test phase			
	small diameter short distance 14/80	small diameter long distance 14/120	large diameter short distance 21/80	large diameter long distance 21/120
Index of Difficulty for adjacent and diagonal movements	**3.01** **3.51**	3.60 4.10	2.43 2.93	**3.01** **3.51**

Part B, the free recall part, informed the participants that the red targets had followed a repeating pattern, but did not mention sequence length. The participants were presented with a figure containing the same four circles as on the touch sensitive screen, and asked to draw the pattern they had executed or parts of it. An example was drawn on the same page. Part C of the questionnaire, the recognition part, showed the participants 12 pictures with different sequence orders. Eight pictures contained a 6-item sequence and four a 12-item sequence. Participants filled in for every picture whether that was the pattern they had executed and how sure they were on a scale of zero (uncertain) to 100 (certain). Finally, Part D of the explicit knowledge questionnaire involved forced choice and showed the participants four figures with the four alternative practiced sequences. Participants were asked to pick out the one they had executed in the practice phase and to indicate how certain they were about this on a 100-point scale.

APPARATUS

Participants tapped the targets with a special stylus on a 17 inch IIYAMA Vision

Master MF8617E monitor. This monitor produced a 640 x 480 pixel VGA image, with a ClearTek capacitive touch-sensitive layer that senses the location of a tap with a resolution of 1024 x 1024 pixels. This touch sensitive screen was mounted in a hole in a table and the screen surface made an angle of about 30° with the table surface. To ensure for every participant the same viewing distance of 45 cm between the eyes and the touch display, participants had their head in a chin and forehead rest while carrying out the task. Data were collected and saved on a 333 MHz Pentium-based PC. This computer controlled the experiment and used Micro Experimental Laboratory (MEL version 2.0) software. The experimenter sat behind the PC to start the experiment and watch whether the participants performed the experiment correctly. As a consequence of system delays, but unnoticeable for participants, RSI varied from 0 to 27 ms.

DATA ANALYSIS

Response times were defined as the time between target onset and hitting the target, thus including reaction times as well as movement times. The first two trials of a block, errors and the two trials following an error were not included in the analyses. Also, response times that were longer than three times the standard deviation from the average response time within a block across participants were excluded from the analyses. The latter was done for the small and large pattern group separately and removed approximately 2% of the data within each block.

5.3.2 Results

AWARENESS GROUPS

The results of the paper awareness questionnaire were used to divide the 48 participants into three awareness groups: aware, partially aware and unaware. Awareness appeared independent of whether participants belonged to the small or large pattern group. The most important part of the questionnaire for determining awareness was part D, in which participants were to choose their own practiced sequence out of four alternatives. 20 participants recognized their sequence and 28 participants did not. Within these two groups participants were rank ordered according to the number of correct transitions they produced by free recall in part B of the awareness questionnaire. The 16 participants with the highest number of correct transitions in the group that recognized their practiced sequence in part D of the questionnaire were considered aware. The 16 participants with the lowest number of correct transitions in the group that did not recognize their practiced sequence were considered unaware. The remaining 16 participants were considered partially aware. Because some participants had the same number of correct transitions, part C of the awareness questionnaire determined what rank order they received. Table 5.2 presents the characteristics of the three awareness groups. These results show that in both the small and large pattern groups explicit sequence knowledge had developed, although the number of aware participants in the large patter group was a bit smaller ($n = 7$ compared with $n = 9$ in the small pattern group). A χ^2-square test showed, that the distribution of awareness did not differ significantly between the small and large pattern group, $\chi^2(2) = 0.5$, $p > .50$. So, awareness development was not significantly influenced by diameter and/or distance during practice.

Table 5.2: Characteristics of the three awareness groups as categorized using the awareness questionnaire results.

Awareness group	Participants selecting the correct statement in questionnaire (Part A)	Mean number of correct transitions (12 max.) (Part A)	Median certainty of identifying the correct sequence (scale 0 - 100) (Part C/D)	Median certainty of identifying the incorrect sequences (scale 0 - 100) (Part C/D)	Participants in centre practice group (n = 24)	Participants in no-centre practice group (n = 24)
unaware (n = 16)	n = 3 (19%)	1.25 (range 0 - 2)	38.0	50.0	n = 8 (33%)	n = 8 (33%)
partially aware (n = 16)	n = 8 (50%)	2.38 (range 0 - 7)	44.0	54.0	n = 7 (29%)	n = 9 (38%)
aware (n = 16)	n = 12 (75%)	6.22 (range 3 - 12)	75.0	60.5	n = 9 (38%)	n = 7 (29%)

According to the certainty scores filled out in part C of the questionnaire; the three awareness groups differed also with respect to their certainty in part C. A Kruskal-Wallis ANOVA on rank orders for certainty of accepting the practiced sequence or rejecting the alternative sequences showed that median certainty rating increased with awareness: executed sequence $H(2, n = 48) = 14.7$, $p < .001$, incorrect sequences $H(2, n = 48) = 7.4, p < .05$).

PRACTICE PHASE

Figure 5.2 shows the response times of the aware and unaware subgroups in the small and large pattern groups during practice. A Group (2: large pattern vs. small pattern) x Awareness (3: aware, partially aware, unaware) x Block (9: blocks 1-9) ANOVA was conducted on the response times of these nine blocks. Group and Awareness were between-subject variables and Block was a within-subject variable. In line with Fitts' law, the large and small pattern groups did not perform differently, $F(1, 42) = 1.1, p > .20$. Awareness was associated with a generally higher execution rate, $F(2, 42) = 4.6, p < .05$, and with larger improvement during practice, $F(16, 336) = 1.9, p < .05$. The group by awareness interaction was not significant, $F(2, 42) < 1, p > .20$, indicating that the effect of awareness was comparable in both groups. The schema theory was confirmed in that mean response times were similar in the small and large pattern groups. Besides, the effect of awareness was comparable in the two groups. In both groups, the response times of the partially aware group were generally in between those of the aware and unaware groups. Therefore, we excluded the partially aware group from further analyses.

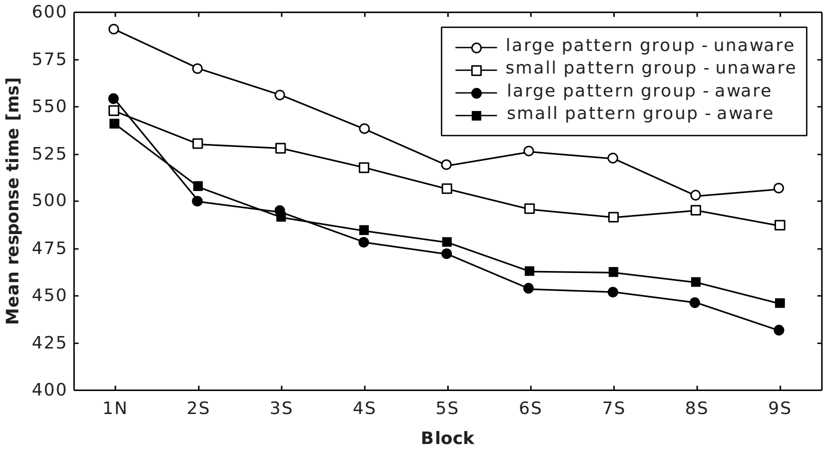

Figure 5.2: Mean response times of the aware and unaware participants in the small and large pattern groups in the nine practice blocks. Block 1 contained a sequence (N) that was different from the sequence used in the other eight blocks (S).

TEST PHASE

Figure 5.3 depicts the results of the eight test blocks separated by pattern group and ID difference. A Group (2) x Awareness (2) x Sequence (2: new vs. practiced) x Diameter (2: large vs. small) x Distance (2: long vs. short) ANOVA was used to analyse the response times of the eight test blocks with Group and Awareness as between-subject variables. The Awareness main effect showed that aware participants generally had shorter response times than unaware participants, *F*(1, 28) = 14.1, *p* < .001. The Group main effect was not significant, *F*(1, 28) = 2.0, *p* > .15, demonstrating that overall participants of the small and large pattern groups did not perform significantly different.

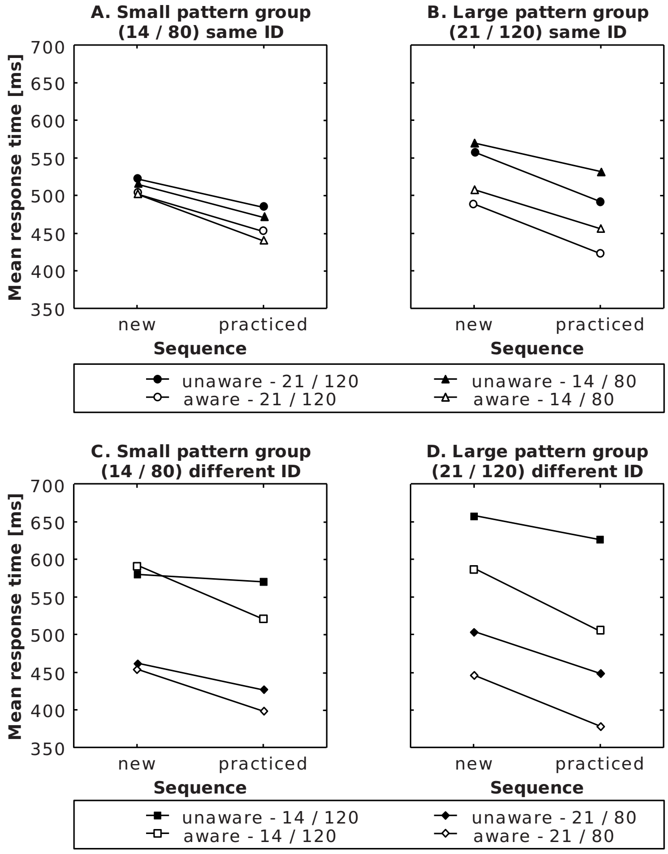

Figure 5.3: Mean response times of the test phase, separated by pattern groups and awareness. The large pattern group practiced with a large diameter and a long distance between the targets, and the small pattern group with a small diameter and a short distance. Panels 5.3A en B show the results of the blocks with the same ID, separated by group. Panels 5.3C and D depict the results of the blocks with a larger (smaller diameter and long distance) or smaller ID (large diameter and short distance).

In the test phase we determined whether implicit and explicit sequence knowledge transferred to conditions with different absolute sizes and the same ID, and to conditions with different IDs. In all comparisons the practiced stimulus order was always relative to the new stimulus order. First, planned comparisons for both pattern groups showed that aware and unaware participants did not perform significantly different in the conditions with the same ID and different absolute sizes, *Fs*(1, 28) < 2.5, *ps* > .12. It appears that implicit and explicit sequence knowledge fully transferred to a different size with the same ID. This is visible in the two upper panels of Figure 5.3: the circle versus the triangle symbols in the left panel for the small and in the right one for the large pattern group.

Second, planned comparisons were executed of the 14/80 (ID as practiced) vs. 21/80 (new ID) condition for the small pattern group, and the 21/120 (ID as practiced) vs. 21/80 (new ID) condition for the large pattern group. This essentially tested transfer to a smaller ID (easier movement) for both pattern groups. (In case of the small pattern group the triangle symbols in the upper left panel of Figure 5.3 were compared with the diamond symbols in the lower left panel. For the large pattern group the circle symbols in the upper right panel were compared with the diamond symbols in the lower right panel.) The comparisons showed that relative to the new sequence both aware and unaware participants separately performed not significantly different in both pattern groups, *Fs*(1, 28) < 1, *ps* > .20, showing that implicit and explicit sequence knowledge fully transferred to a smaller ID.

Third, the condition in which the ID was larger (i.e. more precise movement) was compared with the practiced sequence conditions: that is, 14/80 (as practiced) vs. 14/120 for the small and 21/120 (as practiced) vs. 14/120 for the large pattern group. (In Figure 5.3 the square symbols in the left and right lower panels were compared with respectively the triangle symbols in the upper left panel for the small pattern group and the circle symbols in the upper right panel for the large pattern group.) The results suggested that aware participants in both pattern groups fully transferred their sequence knowledge, *Fs*(1, 28) < 1.1, *ps* > .20. On the contrary (and also relative to the new sequence), the unaware participants in both pattern groups performed differently, *Fs*(1, 28) > 4.0, *ps* < .05. This was tested separately for each group and indicated that unaware participants were unable to fully transfer their sequence knowledge when movements were more precise.

In the same ANOVA, the two pattern groups were compared with each other to find out whether practicing with a large or a small ID affected the use of sequence knowledge differently. The only interaction that reached significance, besides the Awareness x Group interaction, *F*(1, 29) = 4.5, *p* < .05, was the Group x Diameter interaction, *F*(1, 28) = 6.4, *p* = .01. This latter interaction indicated that, across practiced and new sequences, transfer of target hitting skill was higher from small to large diameter than vice versa. When looking at the separate ID conditions, planned comparisons showed that participants in the large pattern group always had longer response times, *Fs*(1, 28) > 3.9, *ps* < .05. Moreover, unaware participants in this group used their sequence knowledge less, *Fs*(1, 28) < 7.5, *ps* < .05. So, regardless of the ID condition they were in, participants in the large pattern group had more difficulties expressing their sequence knowledge. This holds especially for the unaware participants in the large pattern group.

In summary, the results indicated that participants of both the small and large pattern groups generally showed full transfer of sequence knowledge when sizes changed and the ID was the same or different. This supports the schema theory in that performance of the participants remained the same with changing relative spatial layout. There was one exception: Participants without awareness in both pattern groups had limited sequence use with more precise movements (larger ID).

ERRORS

Instead of proportion errors per block we used arcsin transformed error percentages per block, because arcsin transformation distributed percentage data more normally (Winer, Brown & Michels, 1991). A Group (2) x Awareness (3) x Block (9) ANOVA with Block as within-subjects variable on arcsin transformed error percentages in the practice phase demonstrated that participants made relatively few errors in the large group (mean is 2.9% per block) compared to the small group (mean is 6.6% per block), *F*(1, 42) = 40.8, *p* < .001. A Group (2) x Awareness (3) x Sequence (2) x Diameter (2) x Distance (2) ANOVA was conducted on the arcsin transformed error percentages of the test phase. The results confirmed that participants made more errors when the diameter was smaller and the distance was longer (i.e., higher ID), *Fs*(1, 42) > 16.0, *ps* < .001. Furthermore, with a large distance participants made more errors in the blocks with the practiced sequence, while with the short distance more errors were made in the blocks with a new sequence, *F*(1, 42) = 5.9, *p* < .05.

5.3.3 Discussion

In the present experiment, we were mainly interested in two issues. First, whether the notion of a general schema that is adjusted to a particular setting before being carried out (i.e. schema theory) holds for sequence knowledge in the serial RT task with aiming movements. Second, whether this is different for participants with little and those with substantial awareness of the sequence. Therefore, two groups of participants practiced the same sequence though consisting of different aiming movements, but with the same Index of Difficulty (Fitts' law). The small pattern group practiced with a short distance and a small target diameter and the large pattern group with a long distance and a large target diameter. First of all, the data of the awareness questionnaire indicated that in both groups explicit knowledge of the sequence order had developed, and that awareness was not influenced by diameter and/or distance.

According to Fitts (1954), movement time is affected by the Index of Difficulty (ID), which is a function of target distance and size. So, two movements with different target sizes and distances would have the same movement time when ID is identical. The results of the practice phase do support Fitts' law: response times of the large and small pattern groups did not differ significantly. Moreover, the effect of awareness was comparable in both groups. Apparently, during practice awareness develops within both pattern groups, and this development does not differ between the two groups. So, implicit and explicit sequence knowledge do not differ in the pattern groups, although the target distances and target sizes are different. The practice phase thus showed that the ID does not influence response time and Fitts' law holds for sequences of aiming movements that make up a serial RT task.

In the test phase we examined the transfer of implicit and explicit sequence knowledge to different absolute sizes and the same ID, and to different IDs. The results showed that both aware and unaware participants did not perform significantly different in the conditions with the same ID and different absolute sizes. This means that there is full transfer of implicit and explicit sequence knowledge and hence that implicit and explicit sequence knowledge are stored in a relative spatial code.

For both pattern groups implicit and explicit sequence knowledge were also fully transferred to easier movements (smaller ID). This effect occurs for both a smaller ID due to a larger target diameter (small pattern group) and a smaller ID due to a smaller target distance (large pattern group). So, there is full transfer of implicit and explicit sequence knowledge when relative and/or absolute sizes change. The results of the transfer to a smaller ID are not in line with Fitts' law, as one would expect shorter response times when the ID becomes smaller.

In the case of transfer to more precise movements (larger ID) aware participants showed full transfer of their (explicit) sequence knowledge. For the small pattern group this means an increase in the absolute target distance and for the large pattern group a decrease in the absolute target diameter. Again, these results are not in line with Fitts' law: response times were shorter than should be according to the law. A study of Adam et al. (2006) recently also showed an exception to Fitts' law with multi-element displays. In their study, Adam et al. had participants execute rapid hand movements from a starting position to one of seven horizontally aligned target locations from this starting position. In a second experiment the target locations were vertically aligned and the number of targets was five instead of seven. As the diameter of the targets always was 10 mm and only the distance changed, the ID increased with increasing target distance. There were two conditions: the placeholder condition in which the potential target locations were all continuously visible and the no-placeholder condition in which these placeholders were absent. In the latter case the target appeared by itself. The results showed a deviation from Fitts' law in the placeholder condition in both experiments: response times were shorter for the most distant target than should be according to the law. Adam et al. (2006) explain this result in terms of egocentric and allocentric coding in visually guided aiming. When there is only one target area present in the visual field, only egocentric coding influences the spatial and temporal information. On the contrary, when there are multiple target areas in the environments, as is the case with the present experiment, the visual control may be influenced by both allocentric and egocentric spatial information. In the latter case the target areas act as distractors according to Adam et al. (2006). One question that can not be answered is why the present experiment found both longer (easier movements; ID smaller) and shorter (more precise movements; ID larger) response times than expected by Fitts' law, while Adam et al. (2006) only found shorter response times than expected.

Unaware participants, in both the small and large pattern group, were unable to fully transfer their sequence knowledge to more precise movements (larger ID). This effect thus occurs for both more precise movements due to a longer target distance (small pattern group) and more precise movements due to a smaller diameter (large pattern group). When the movements became more precise, response times of unaware participants were longer, just as one would expect according to Fitts' law.

The results of the practice phase support the schema theory: response times of both aware and unaware participants are not significantly different with relative movements. The test phase results also largely support the schema theory. Only implicit sequence knowledge is not fully transferred to more precise movements in this phase. This counts for both the large and small pattern group. It seems that the underlying implicit and explicit representations are spatial and that hierarchical models of motor skill explain the exception of less transfer with more precise movements for unaware participants.

In conclusion, the results of the present experiment show that transfer of implicit and explicit sequence knowledge to other ID conditions is full, except for implicit sequence knowledge when more precise movements are needed. In this latter case the response times are longer with transfer to a new and larger ID; which is in line with Fitts' law. Concerning the schema theory, the results largely show full transfer with relative movements. It seems that these more precise movements are difficult for participants with implicit sequence knowledge. Apparently, implicit knowledge is less flexible than explicit knowledge in that the execution of more precise movements interferes with implicit but not with explicit sequence knowledge.

Chapter 6

Implicit and explicit knowledge play no role when a practiced aiming movement sequence is rotated or point-mirrored

6.1 Abstract

The present study concerned whether implicit and explicit knowledge of sequential aiming movements are transferred to spatially distorted versions of a practiced serial RT (reaction time) sequence. Following practice of a particular sequence, participants conducted four different test blocks containing: 1) the practiced sequence; 2) a rotated version of the practiced sequence; 3) the point-mirrored version of the practiced sequence; or 4) a new sequence. The results demonstrate that both implicit and explicit sequence knowledge developed in the practice phase. However, during the test phase there was no transfer of either implicit or explicit sequence knowledge to the rotated or point-mirrored sequence, rejecting the notion that spatial sequence representations contribute to changed spatial lay outs.

6.2 Introduction

Implicit learning has been studied in the field of cognitive psychology since Reber's work on artificial grammar learning (Reber, 1967, 1969). The knowledge gained with implicit learning is not fully accessible to consciousness: people who are unable to verbalise what they have learned are said to have implicit knowledge. In the literature it is argued that despite this inability to tell about it, the knowledge represented could be transferred or generalized to novel stimuli (e.g. Reber, 1989; Seger, 1994; Sun, Slusarz & Terry, 2005). In artificial grammar learning, novel stimuli refer to new strings of letters that conform to the grammar participants had learned; the stimuli (letters) themselves had the same physical characteristics. In the present experiment we will also refer to "new strings of stimuli". On the contrary, explicit knowledge is knowledge people are aware of: they can tell what they have learned and this knowledge is not as easily transferred or generalized to novel stimuli. The present study is conducted to find out whether implicit knowledge can indeed be transferred or generalized more easily to novel stimulus orders than explicit knowledge.

Implicit learning has, in the case of spatial movement patterns, been studied with the serial RT task introduced by Nissen and Bullemer (1987). In the typical serial RT task, participants see four horizontally aligned stimuli on a computer screen. When one of the stimuli sets on, they react by pressing the spatial compatible key on a keyboard. In the standard version of this task, 200 ms after the onset of the response the next stimulus is presented. So, the response to stimulus interval (RSI) is 200 ms. Then another key is pressed and so on. Usually, the stimuli cycle through a fixed order of 10 to 12 stimuli and participants practice this response order but are not told about it. Sequence knowledge is demonstrated by shorter response times for the practiced stimulus order compared with a random, pseudorandom or new stimulus order.

A few studies with the keying serial RT task used a mirror sequence in the transfer phase (Deroost, Zeeuws & Soetens, 2006; Grafton, Hazeltine & Ivry, 2002; Verwey & Clegg, 2005; Wachs, Pascual-Leone, Grafman & Hallett, 1994). This sequence was the mirror image of a practiced sequence that had to be executed with the other hand. In this way, the response sequence required homologous finger movements to those produced with the other hand in the practice phase. According to Verwey and Clegg (2005), two mechanisms may be responsible for transfer of sequence knowledge. The first is a spatial (effector-independent) representation, which predicts similar transfer to the mirror sequence for the practiced and unpracticed hand. A second mechanism is a motor level (effector-dependent) representation that predicts better performance of the mirror sequence than a random sequence for the unpracticed than for the practiced hand. Their study showed that (1) performance of the mirror and practiced sequences was significantly better than with random stimuli with both hands, suggesting that (2) both spatial and motor representations develop, and (3) effector-dependence is based on implicit knowledge of the sequence. So, it seemed that sequence knowledge is in a code that can be used with mirror sequences too, irrespective of the hand used.

The aim of the present study was to find out whether in a serial RT task with aiming movements implicit sequence knowledge transfers more easily to spatially transformed sequences than explicit sequence knowledge. Earlier research with the keying serial RT task showed that (line-)mirrored sequences benefit from practice and we wondered whether rotated and point-mirrored sequences of aiming movements would also benefit from practice. That would indicate that the developed representation is spatial (Verwey and Clegg, 2005). Therefore, we had participants practice a sequence of aiming movements. Participants were then transferred to a test phase that consisted of four blocks, each containing nine repetitions of either the practiced sequence, the point-mirrored sequence, the rotated sequence or a new sequence. According to earlier studies that used keying sequences, the transfer of implicit sequence knowledge towards other stimulus orders might be easier than that of explicit sequence knowledge (e.g. Reber, 1989; Seger, 1994; Sun, Slusarz & Terry, 2005). In the present study the point-mirrored, rotated and new sequences all contained novel orders of stimuli. So, the expectation would then be that the transfer of sequence knowledge to these sequences is larger for implicit than explicit sequence knowledge. As earlier studies (e.g. Verwey & Clegg, 2005) showed transfer to a mirrored sequence with keying sequences, we expected there might be transfer to rotated and point-mirrored patterns with a more spatial (aiming) version also. Transfer to mirrored patterns means there might be storage in terms of a direction-aspecific code and we wanted to find out whether this would also be the case for transfer to rotated and point-mirrored patterns.

In addition, the study of Ter Schegget and Verwey (2009a) suggested that the more aware participants used the 200 ms RSI in the practice phase of Experiment 1 to move their hand immediately to the next target, whereas less aware participants seemed to first move their hand to a strategic location from where the distance to all target areas was equal. The present study used also a 200 ms RSI as we wanted to replicate this effect. In short, the present study focused on the extent that implicit and explicit sequence knowledge transfer to novel stimuli.

6.3 Experiment

6.3.1 Method

PARTICIPANTS

In exchange for course credits, the present experiment tested 36 right-handed students of the University of Twente, 24 male and 12 female. They had never participated in a sequence learning experiment before. All participants had normal or corrected to normal vision and gave informed consent before the experiment started.

TASK

Participants were presented with four circular target areas with a diameter of 32 mm on a black background of a touch sensitive screen. The target areas formed an imaginary diamond with four equally sized sides, and their centres were at a distance of 65 mm from the diamond centre. Therefore, the distance between the centres of two adjacent target areas was 92 mm and the distance between two opposite target areas 130 mm. One of the target areas, the target, consisted of a white inner circle of 17 mm with a red ring around this inner circle (see Figure 6.1). Participants were asked to hit the white inner circle of the target as fast as possible with a special stylus. The response to stimulus interval (RSI), the time between touching a target and the lighting of a new target, was 200 ms. Immediately after participants had touched the target it changed into a white target area and another target area turned into target as it consisted of a white inner circle with a red ring around it. Therefore, a particular area never became target twice or more after each other.

We only used four 12-item second-order conditional (SOC) sequences in the present experiment. It is only possible to predict an item in these sequences, when you know the two prior target locations (Schvaneveldt & Gomez, 1998). For instance, in the basic sequence 124132342143 the "12" stimulus pair is always followed by a "4". All sequences that were used were structurally identical. First, the location frequencies were alike: each of the four target areas was used as target three times. Second, the sequences were the same with respect to the first-order transition frequency: each target area was preceded once by each of the other three target areas. Third, there were no repetitions in any of the SOC sequences. Finally, every sequence contained one reversal ("323" in the basic sequence). The consequence of the use of SOC sequences was that improvement was not caused by learning stimulus frequencies or pair frequencies.

As all participants were right-handed, it was possible that the right or lower target area were sometimes occluded by that hand. To distribute these effects of the right hand across all sequence elements, one group of participants tapped the basic sequence and three other groups tapped a rotated version of this sequence (231243413214, 342314124321, and 413421231432).

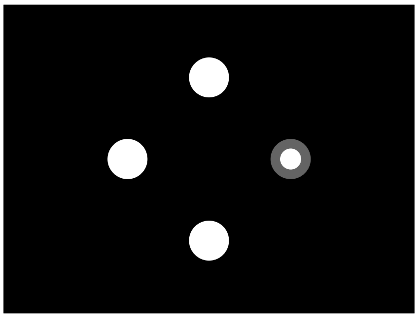

Figure 6.1: Example of the touch screen appearance during the experiment. Participants had to touch the white inner circle of the red target area.

PROCEDURE

Participants started filling in a consent form, and then received written instructions extended with oral explanation before the experiment started. Both speed and accuracy were stressed as being important. The sequential order was not mentioned. Therefore, participants did not know they practiced a sequence beforehand. After receiving the instructions, participants practiced one session of 108 taps. These taps together made up nine repetitions of a 12 items SOC sequence.

The experiment consisted of fourteen blocks. Except for the first block, Blocks 2-9 of the practice phase used the same SOC sequence. The first block was different, to have the participants getting used to the experimental setting and to prevent them from searching for an order. Each block was initiated by the message to get ready and after a short delay the 108 trials were presented to the participants. To keep accuracy high, errors were "punished" with a waiting time of 1500 seconds. After each block, information about participants' performance was displayed on the screen. This feedback consisted of the mean RT and accuracy values of the last executed block. The order of the four blocks of the test phase was balanced across participants. One test block used the same sequence that was practiced in the practice phase. A second test block contained a new SOC sequence. The third and fourth test blocks consisted respectively of a 90º rotated and point-mirrored version of the practiced SOC sequence. For instance, when participants practiced the sequence 231243413214 during the Blocks 2-9, the rotated sequence was 342314124321 and the point-mirrored sequence 413421231432. Inevitably, because of the experimental setting with four target areas, within a participant stimulus fragments in the practiced, rotated, point-mirrored and new sequences sometimes contained the same stimulus fragments. These same stimulus fragments contained at most four stimuli. However, this occurred also in the earlier studies. For example Verwey and Clegg (2005) had participants cycle through a 10-element sequence. One participant in their Experiment 1 practiced the sequence 5465645654, the mirrored sequence was 5645465456 and the new sequence 6546456465. So, in all sequences this participant executed for instance the stimulus fragments 546 and 465. Finally, Block 14 of the present experiment was the same as the Blocks 2-9 in the practice phase.

Participants filled out a knowledge questionnaire after the final block. The questionnaire was used to divide all participants in three different awareness level groups. The questionnaire was given on a piece of paper, on which participants wrote their answers. Part A included an introduction to the order of targets that appeared in the experiment, and asked the participants to choose the best fitting of six descriptions about the order in which the targets appeared. The descriptions were: (1) the order was random; (2) some positions occurred more frequently than other positions; (3) my hand tended to go a certain direction; (4) the order was often predictable; (5) the same order occurred more than once; (6) the same order occurred throughout the whole experiment.

Part B of the questionnaire involved informing participants that there actually was a pattern in the appearance of the red targets. They were asked to draw any pattern, or parts of it, that they had noticed or suspected. An example of how this should be done was drawn on the same page. Part C showed 12 pattern figures and asked participants for each figure whether this was a pattern they had been exposed to during the experiment. Participants also rated on a scale of zero (uncertain) to 100 (certain) how sure they were about this. Part D of the questionnaire presented the participants with the four alternative practiced sequences. They were asked to pick out the one they had been executing and, again, to fill out for all four descriptions how sure they were about this. All participants filled out the questionnaire in the same order. It was not allowed to look back and forth between the sheets of the questionnaire, or to make corrections or changes. So, the questionnaire was based on combining measures of participants' awareness of the sequence (recognition) and their ability to draw the order of the stimuli (recall).

APPARATUS

The targets were displayed and tapped on a 17 inch IIYAMA Vision Master MF8617E monitor producing a 640 x 480 pixel VGA image, with a ClearTek capacitive touch-sensitive layer that senses the location of a tap with a resolution of 1024 x 1024 pixels. Participants sat behind this touch sensitive screen with their head in a chin and forehead rest. This ensured for every participant the same viewing distance, namely 45 cm, between the eyes and the touch sensitive screen. The screen was adjusted in a hole in a table, and made an angle of 30° with the table surface. A special stylus was used to tap the targets. The touch sensitive screen was connected to the control computer, a 333 MHz Pentium-based PC. The experimenter sat behind this control computer to run the experiment, and at the same time to watch the participants performing the experiment. This computer used Micro Experimental Laboratory (MEL version 2.0) software to control the experiment and save performance data. Due to system delays, but unnoticeable for participants, RSI varied from 0 to 27.

DATA ANALYSIS

Response times were the times between target onset and hitting that target. This means that in the present experiment response times are really a combination of response time and movement time. The average response times and error proportions per participant per block were analyzed. The first two trials of a block, errors and the two trials following an error were not used. Also, response times that were longer than two times the standard deviation from the average response time within a block across participants were excluded from the analyses. This latter calculation removed approximately 2% of the data within each block.

6.3.2 Results

AWARENESS GROUPS

The awareness questionnaire was used to divide participants into three awareness groups: aware, partially aware and unaware. First, part D of the questionnaire, in which participants were asked to choose their practiced sequence out of four options, was used to divide the participants into two groups. This division was based on whether they chose their practiced sequence or not. Second, part B of the questionnaire, in which participants were asked to draw the sequence or parts of it, was used to rank order the participants within these two groups. Third, parts C and D of the awareness questionnaire were used to distinguish participants that had the same rank order. The 12 participants who recognised the sequence and had the highest rank order were called the *aware group*. The 12 participants who had not recognised the sequence and had the lowest rank order were called the *unaware group*. The remaining 12 participants formed the *partially aware group*. Table 6.1 displays the characteristics of the three awareness groups.

A Kruskal-Wallis ANOVA on certainty rank orders (parts C and D of the questionnaire) showed that certainty increased with ranked awareness, for the executed sequence $H(2, n = 36) = 13.7, p < .01$, and for incorrect sequences $H(2, n = 36) = 7.8, p < .05$. Moreover, the results of parts A and B of the questionnaire also underlined the division into the three awareness groups: most aware participants chose the correct description in the experiment ($n = 9$, 75%, part A of the questionnaire) and aware participants had the highest mean number of correct transitions (6.75) on part B of the questionnaire.

Table 6.1: Characteristics of the three awareness groups according to the questionnaire results.

Awareness group	Participants selecting the correct statement in questionnaire (Part A)	Mean number of correct transitions in sequence drawn of 12 (Part B)	Median certainty of identifying the correct sequence (scale 1 - 100) (Part C)	Median certainty of identifying the incorrect sequences (scale 1 - 100) (Part C)
unaware (*n* = 12)	*n* = 3 (25%)	2.00 (range 0 - 4)	38.0	46.0
partially aware (*n* = 12)	*n* = 5 (42%)	3.78 (range 0 - 8)	42.5	50.0
aware (*n* = 12)	*n* = 9 (75%)	6.75 (range 2 - 11)	81.5	79.0

PRACTICE PHASE

The mean response times of the three awareness groups in the nine practice blocks are shown in Figure 6.2. An Awareness (3: aware, partially aware, unaware) x Block (8: Blocks 2-9) x Distance (2: small vs. large) ANOVA was carried out on the eight practice blocks with the same sequence. The results showed that aware participants performed fastest, while unaware participants performed slowest, $F(2, 33) = 8.9$, $p < .001$. Furthermore, a planned comparison showed that aware participants improved more than unaware participants during the practice phase, $F(1, 33) = 16.4$, $p < .001$, showing that explicit knowledge improved performance. Finally, the Distance main effect was significant, $F(1, 33) = 18.3$, $p < .001$, indicating that the movement to an adjacent target (small distance) was executed faster than to an opposite target (large distance). Figure 6.2 and Table 6.1 clearly show the differences between the three awareness groups. As we were interested in the difference between implicit and explicit sequence knowledge, in further analyses the partially aware group was left out.

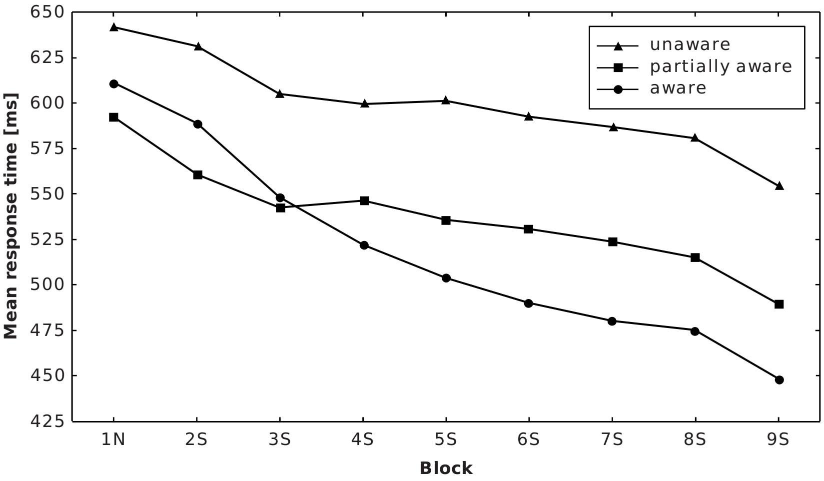

Figure 6.2: Mean response times of aware, partially aware and unaware participants in the nine blocks of the practice phase. The first block had a sequence that was different (N) from the other eight blocks (S).

TEST PHASE

An Awareness (2: aware vs. unaware) x Sequence (4: practiced, new, rotated, point-mirrored) x Distance (2: small vs. large) ANOVA, with Sequence and Distance as within subjects variables, was executed on the mean response times of the test phase. Figure 6.3 pictures the results of the test phase. The results showed that awareness was associated with a higher execution rate, *F*(1, 22) = 15.6, $p < .001$. Moreover, the awareness by sequence interaction was significant, *F*(3, 66) = 4.6, $p < .01$, indicating that the effect of awareness was different in the four sequence conditions.

Planned comparisons showed that both aware and unaware participants had shorter response times in the block with the practiced sequence than in the other three sequence conditions, *Fs*(1, 22) > 15.1, *ps* < .001. There was no difference between the rotated and point-mirrored block for both aware and unaware participants, *Fs*(1, 22) < 1, *ps* > .20. Finally, aware participants had shorter response times in the new sequence than the rotated and point-mirrored sequence, *Fs*(1, 22) > 11.3, *ps* < .01, while unaware did not perform differently in these blocks, *Fs*(1, 22) < 1, *ps* > .20. All results are clearly visible in Figure 6.3.

The Distance main effect was significant, *F*(1, 22) = 11.5, *p* < .01, as was the Sequence x Distance interaction, *F*(3, 66) = 3.0, *p* < .05. Planned comparisons were used to find out what caused this interaction. The comparisons showed that only within the practiced sequence block the small distance was executed faster than the large distance for both aware, *F*(1, 22) = 11.7, *p* < .01, and unaware participants, *F*(1, 22) = 4.3, *p* = .05. However, a planned comparison showed that aware participants did not use their sequence knowledge more or better than unaware participants in the small compared with the large distance, *F*(1, 22) < 1, *p* > .20. Apparently, after hitting a target correctly, both aware and unaware participants moved their hand towards the next target location during the RSI of 200 ms. In the

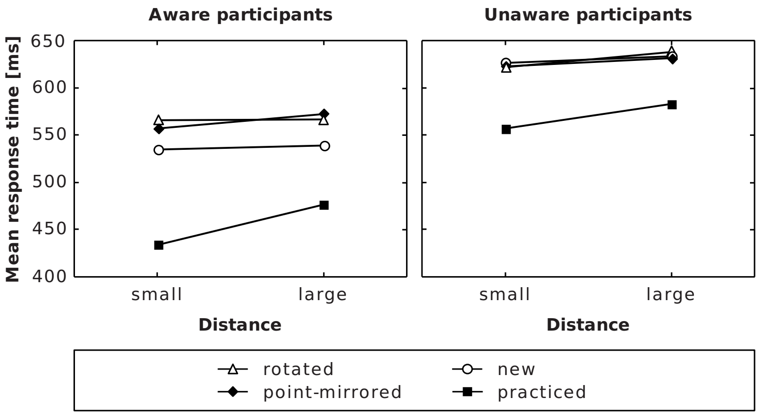

Figure 6.3: Mean response times of aware (left panel) and unaware (right panel) participants in the four test blocks, separated for distance.

new, rotated and point-mirrored block there is no difference in performance between the small and large distance for both aware and unaware participants, *Fs*(1, 22) < 2.7, $p > .11$. It seems that all participants now move their hand to a strategic point during RSI, from where the distance to all target areas is the same.

A planned comparison showed a significant interaction between the practiced versus the new sequence and distance, $F(1, 22) = 5.6$, $p < .05$. This suggests that participants did not learn the new sequence. However, the interaction between awareness and the practiced versus the new sequence did not reach significance, $F(1, 22) = 1.3$, $p > .20$, showing that explicit sequence knowledge did not strengthen this immediately going to the next target in practiced sequences.

ERRORS

A Block (8) x Awareness (3) ANOVA was carried out on the arcsin transformed error percentages of the eight blocks in the practice phase. The analysis showed no significant effects. The error percentages of the four blocks in the test phase (mean 3.6%) were analyzed with an Awareness (3) x Block (4) ANOVA. Again, there were no significant effects.

6.3.3 Discussion

We investigated whether there is transfer of implicit and/or explicit sequence knowledge with aiming movements to rotated and point-mirrored versions of a learned sequence. More specifically, in the present study we wondered whether participants could transfer their sequence knowledge to a rotated or point-mirrored pattern. First of all, the results of the knowledge questionnaire and the practice phase showed that participants developed implicit and explicit sequence knowledge of the pattern of aiming movements.

The results of the test phase showed that participants were unable to transfer their implicit and explicit sequence knowledge to the rotated or point-mirrored version of the practiced sequence. This contrasts with Verwey and Clegg (2005), who found that the mirror sequence was carried out faster than a new sequence even with the practiced hand. They therefore conclude that an abstract sequence representation is in a code that can be easily mirrored. However, in their study participants practiced keying sequences and in the present study participants practiced an aiming movement version of the serial RT task.

A possible explanation for the finding that there was no transfer of sequence knowledge to the rotated and point-mirrored version comes from a study of Elsner, Kunde and Kiesel (2008). In their study, participants were transferred in four experiments to novel stimulus orientations and identities. Stimuli were digits and letters which were presented in different orientations (inverted, upright or horizontal). The results showed that there was only limited transfer to these novel stimulus orientations. The writers suggest that unpracticed novel stimulus orientations hinder participants to transfer their implicit knowledge of the practiced stimulus orientations. The same might have happened in the present study. Participants practiced with a certain stimulus order and were then confronted with a stimulus order that was new to them. They did not "recognize" the new order as a rotated version of the practiced stimulus order. Apparently, participants do not automatically rotate the abstract representations.

An interesting finding concerned the slower response times of aware participants for both the rotated and point-mirrored sequence compared with the new sequence. This was probably caused by some stimulus fragments that were the same in the practiced and rotated or point-mirrored sequences within a participant. The new sequence had almost no overlapping stimulus fragment with the practiced, rotated or point-mirrored sequences. We were unable to avoid this because of the experimental setting. Although these stimulus fragments appeared seldom and existed only of four items at the most, it might have confused participants in that they recognized a part of their practiced sequence. However, earlier studies in which participants were confronted with the serial RT task also used this overlap of stimulus fragments (e.g. Verwey & Clegg, 2005) and yet they did found that the mirrored sequence was executed faster than the new one. So, with keying sequences participants are able to transfer their implicit and/or explicit sequence knowledge, while this is not the case with aiming movement sequences. Apparently it is too difficult or even impossible to transfer spatial representations with aiming movements than with finger pressing movements.

In an earlier experiment (Ter Schegget & Verwey, 2009a), we found that aware participants immediately moved their hand to the next target during the RSI of 200 ms. In contrast, unaware participants moved their hand to a strategic middle point from which the distance to all target areas was equal. The results of the test phase in the present study suggested that with the practiced sequence both aware and unaware participants moved their hand immediately to the next target during the 200 ms RSI. A possible explanation for this result is that the unaware participants in the present experiment had more explicit sequence knowledge than the participants in the earlier experiment. This explanation is closely connected to the number of targets: The earlier study used six targets and the present study four targets. It might therefore be that unaware participants in the present study are more easily able to develop explicit sequence knowledge about the sequence order.

In conclusion, in the present study participants gained implicit and/or explicit sequence knowledge of an aiming movement sequence. When transferred to rotated or point-mirrored versions of the learned sequence, participants were unable to use their implicit and/or explicit sequence knowledge. So, it is impossible for aware and unaware participants to use abstract representations of a learned sequence in a situation where the sequence is rotated or point-mirrored.

Chapter 7

Summary and conclusions

7.1 Summary

In this thesis we investigated implicit and explicit sequence learning with aiming movements. The ability to learn and produce sequential actions is one of the hallmarks of human cognition. Indeed everyone recognizes that many of the tasks performed in everyday life are organized in sequences. For example, when driving a car you first have to fasten the belt. Then you must step on the clutch-pedal and turn the handbrake down, and so on. So, you must switch between different tasks in a prescribed order and you are aware of learning how to drive a car. If you learn the driving task well, this behaviour becomes more or less autonomous. Apparently, by then you have learned the order of the tasks required to control a car. This knowledge is partly implicit as the driver is often unaware of the precise order of the individual movements that he or she is executing when driving the car.

Implicit sequence learning has mostly been studied with the serial reaction time (RT) task (Nissen & Bullemer, 1987). In the typical serial RT task participants sit behind a computer screen on which four horizontally aligned targets are visible. When an asterisk appears above one of the targets, participants immediately press the spatially compatible key on a keyboard. When the correct key is pressed, the asterisk disappears and, after a certain time interval, the next asterisk appears above another target and so on.

In all studies in this dissertation, participants performed an aiming movement version of the serial RT task. They sat behind a touch screen that was mounted in a table. The target areas were white circles and they turned into target when a red outer ring was placed on top of the white circle. In most experiments participants were to touch the white centre circle with a stylus in their right hand (in one experiment they were allowed to touch both the white centre and/or the red outer ring). Unknown to the participants, the targets followed a specific order, together making up a sequence of 12 stimuli. This sequence was repeated without recognizable start or end. After practicing this sequence for 72 cycles in the practice phase, the test phase started. In every chapter the manipulations in the test phase differed.

When participants had finished the last block of an experiment, they filled out an awareness questionnaire. The questionnaire was used to divide the participants into three different awareness groups (aware, partially aware and unaware) and consisted of four parts. In part A participants were asked whether they had noted anything special during the experiment. Part B of the questionnaire, the free recall part, explained participants that they had executed a certain movement order during the experiment, without mentioning the sequence length. Participants were asked to draw this order, or parts of it. In parts C and D of the awareness questionnaire, the recognition and forced recognition parts, drawings of (parts of) the sequences used in the studies were shown. Participants indicated whether they executed the (parts of the) sequence and how sure they were about this.

The results of all studies showed that awareness varied amongst participants, even though performance always improved. This indicates that explicit knowledge does not always develop with these aiming movement sequences, while implicit knowledge develops always.

7.2 Conclusions

The five empirical studies in this dissertation were executed to unravel some of the mechanisms underlying implicit and explicit sequence learning with sequential aiming movements. At the outset, we were not sure whether implicit and explicit sequence knowledge would develop just like in the keying version of the serial RT task. One important conclusion of the research reported in this dissertation is that, in line with findings with the version of the serial RT task in which keys are pressed in a fixed order, all participants improved when repeatedly tapping targets in a fixed order. Furthermore, like in the keying serial RT task a substantial part of the participants developed awareness of the order in which they tapped targets, thus developing explicit sequence knowledge, whereas other participants did not develop any clue as to the order in which they had been tapping the targets. Given the improvement these unaware participants showed, they are said to have developed just implicit sequence knowledge.

We were especially interested in possible interference between control of sequences and control of individual aiming movements and posed three hypotheses in Chapter 2. This issue can not be investigated with key press movements, but was expected to provide important information as to the processes involved in ordering movements and executing movements. The three hypotheses differed in whether interference occurs between control at the sequence level (i.e., selecting each next element) and control of individual aiming movements. When these processes do not interfere, these processes can concur and there is less need to perform sequential control during the response to stimulus interval (RSI) than when these processes need to be carried out serially. These hypotheses were tested by manipulating target size and RSI on the assumption that development and application of sequential knowledge would be more or less sensitive to lengthening RSI at different target diameters. Moreover, we were interested whether these findings would differ for participants who were aware and unaware of the sequence order, as that could indicate that interference between aiming movements and sequencing would differ for implicit and explicit knowledge.

The results of the test phases of both Chapters 2 and 3 concur in showing that aware participants benefited from a longer RSI. This is in line with the hypothesis that they needed RSI to apply their explicit sequence knowledge and could not do so during execution of the preceding aiming movement. Therefore, the results of Chapters 2 and 3 support the hypothesis that application of explicit sequence knowledge interferes with the execution of aiming movements.

With respect to unaware participants, the two experiments in Chapter 2 showed that, irrespective of target size, sequence knowledge was applied with RSI 0 and this did not improve with longer RSIs. This indicates that implicit sequence knowledge can be applied during the preceding movement, and supports the hypothesis that assumes no interference between control of element order and of aiming execution. In contrast, the results of Chapter 3 showed that unaware participants did benefit from a longer RSI, thus supporting the notion that sequence knowledge is not entirely applied during the execution of an aiming movement. Explanations for this difference between both studies include unaware participants having some explicit knowledge too (which was applied only after completing a movement), or a smaller number of target areas in Chapter 3 (and as a consequence of this, the higher number of possible next moves). Also, implicit knowledge may have been of more benefit with the larger target diameters in Chapter 2.

These findings indicate that the processing of explicit sequence knowledge interferes with executing movements to small and large targets, but they are ambiguous as to whether processing of implicit sequence knowledge interferes with the control of aiming movements. Importantly, sequence knowledge developed irrespective of target diameter in aware and unaware participants suggesting that, in contrast to the application of implicit and explicit knowledge, the development of implicit and explicit sequence knowledge is not hampered by executing aiming movements.

The results of the second experiment in Chapter 2 suggested also that target diameter influences application of explicit sequence knowledge. In the case of the smaller targets, the results showed no interference of the processing of explicit sequence knowledge with the control of aiming movements. It seems that the longer duration of movements to the smaller targets is used for applying sequence knowledge. However, with the larger targets, the results showed that aware participants were not even able to apply their explicit sequence knowledge when the RSI was 400 ms. These data demonstrate that aware participants have to learn to apply their explicit sequence knowledge during RSI.

A second issue in the present dissertation concerns the transfer of implicit and explicit sequence knowledge to various different situations. We first pursued an indication in Chapter 2 that unaware participants may have moved their hand to a central position after hitting each target. This is a reasonable strategy when one does not know where to move next. Yet, it also suggests that moving to this centre target does not hamper development of (at least) implicit sequence knowledge. To examine this notion explicitly, we included in Chapter 4 for one group of participants a central target to which participants were to move after tapping each regular target. The results confirmed that not only implicit, but also explicit sequence developed despite the need to repeatedly move to this central target. Nonetheless, removing or introducing the central target in a test phase appeared to did hamper transfer. The only exception was when the centre target of the practice phase was removed with unaware participants. This can be easily explained by the notion that removing the centre target did not actually change the task for these participants: They may have continued moving their hand to the centre position despite removal of the centre target, just as in Chapter 2. These findings indicate that the movement to the central target can be included in implicit and explicit sequence representations without affecting sequence learning. Still, these movements seem to be an important part of the representation as removing or introducing the need to move to a central target does influence usefulness of the developed sequence representation, perhaps due to the need to consciously change the automated movement pattern.

In order to examine schema theory (Schmidt, 1975) for the situation that implicit and explicit sequence knowledge is applied, we manipulated in Chapter 5 absolute and relative target diameters and distances. The results confirmed Fitts' law in that movement times did not change when absolute sizes were altered as long as Fitts' law was obeyed (see Fitts, 1954). More importantly, the results largely support the notion that sequence knowledge can be applied to situations with different absolute size but the same relative spatial arrangement, suggesting that movement distance can be set like a parameter as assumed by schema theory. Only participants without explicit knowledge appeared to suffer when movements were more precise (i.e., IDs became larger). The need to perform unusually precise movements seems to have interfered with application of implicit sequence knowledge.

Given earlier findings in the keying version of the serial RT task (Verwey & Clegg, 2005) that sequence knowledge transferred to mirror sequences, we examined in Chapter 6 whether implicit and/or explicit sequence knowledge is perhaps in a format that allows easy transfer to a somewhat different spatial layout. In particular we examined transfer to a rotated version and a point-mirror version of the sequence. Obviously, such changes are possible with the present 2-dimensional stimulus and response arrangements and not with the 1-dimensional arrangements typical for the keying version of the serial RT task. In contrast to the findings by Verwey and Clegg (2005), the results indicate no transfer to these changed layouts, refuting for the aiming version of the serial RT task the notion that implicit or explicit sequence knowledge is in a code that can be used with changed spatially layouts too.

In conclusion, the results reported in this dissertation concur in demonstrating that the development of implicit and explicit sequence knowledge is very similar to the sequential knowledge found with key press movements. Furthermore, they show that when executing aiming movement sequences there is

1) substantial interference between the application of explicit sequence knowledge and the control of aiming movements, 2) some task dependent interference between the application of implicit sequence knowledge and the control of aiming movements, and 3) development of implicit and explicit sequence knowledge is not hampered by the need to also control aiming movements, irrespective of their precision though application of explicit knowledge needs to be learned. In addition, 4) the need to move to a central target after hitting a regular target does not influence the capacity to develop implicit and explicit sequence knowledge, but the movements to these central targets are an important part of the sequence representation and removing or introducing the need to move to a central target does reduce the usefulness of the developed sequence representation. 5) The notion that implicit and explicit sequence knowledge can be used in larger and smaller spatial layouts, as suggested by schema theory, was largely confirmed, except that when movements are more precise the application of implicit sequence knowledge may be hindered. Finally, 6) unlike suggestions with a keying version of the serial RT task, implicit and explicit sequence knowledge can not be applied when the 2-dimensional layout of the aiming version of the serial RT task is changed.

Samenvatting en conclusies

Samenvatting

In deze dissertatie hebben we onderzoek gedaan naar impliciet en expliciet leren bij gerichte bewegingen. Het vermogen om sequentiële handelingen te leren en verrichten is één van de kenmerken van menselijke cognitie. Het is voor iedereen wel herkenbaar dat veel taken die we in het dagelijkse leven uitvoeren in een volgorde georganiseerd zijn. Wanneer u bijvoorbeeld auto gaat rijden, dan doet u eerst de gordel om. Vervolgens trapt u de koppeling in, doet u de handrem er af, enzovoort. In dit voorbeeld moet u schakelen tussen verschillende taken in een voorgeschreven volgorde, en u bent zich er bewust van dat u leert autorijden. Op het moment dat u goed auto kunt rijden, dan wordt dit gedrag min of meer autonoom. Blijkbaar hebt u op dat moment de noodzakelijke volgorde van taken van het autorijden geleerd. Deze kennis is gedeeltelijk impliciet, omdat de chauffeur vaak onbewust is van de individuele bewegingen die hij of zij uitvoert tijdens het autorijden.

Het impliciet leren van een volgorde is voornamelijk onderzocht met de zogenaamde seriële reactie tijd (RT) taak (Nissen & Bullemer, 1987). In de typische seriële RT taak zitten proefpersonen voor een beeldscherm. Op dit scherm zijn vier op een horizontale lijn liggende doelen zichtbaar. Zodra er een sterretje boven één van deze doelen verschijnt, drukken proefpersonen op de ruimtelijk overeenkomstige toets op een toetsenbord. Wanneer de juiste toets is aangeslagen, verdwijnt het sterretje en, na een pauze, verschijnt het volgende sterretje boven een ander doel enzovoort.

In alle studies in deze dissertatie hebben proefpersonen de seriële RT taak met gerichte bewegingen uitgevoerd. Ze zaten voor een in een tafel gemonteerde touchscreen. De doelgebieden waren witte cirkels, die in doel veranderden door het plaatsen van een rode ring op de witte cirkel. In de meeste experimenten moesten de proefpersonen de witte binnenste cirkel aanraken met een pen in de rechterhand (in één experiment mochten de proefpersonen zowel de witte kerncirkel als de rode ring aanraken). De proefpersonen wisten niet dat de doelen in een volgorde werden aangeboden, namelijk een sequentie van 12 stimuli. Deze sequentie werd herhaald zonder een herkenbaar begin of einde. De proefpersonen oefenden deze sequentie 72 keer, waarna de testfase begon. De manipulaties in de testfase verschilden in ieder hoofdstuk van deze dissertatie.

De proefpersonen vulden een vragenlijst in, zodra ze het laatste blok van een experiment uitgevoerd hadden. De vragenlijst bestond uit vier delen en werd gebruikt om de proefpersonen in drie verschillende groepen in te delen, afhankelijk van of ze zich bewust, gedeeltelijk bewust of onbewust zijn van de volgorde. In deel A werd aan proefpersonen gevraagd of ze iets speciaals hadden opgemerkt gedurende het experiment. Deel B van de vragenlijst, het zogenaamde "free recall" deel, vertelde de proefpersonen dat ze de bewegingen in een bepaalde volgorde uitgevoerd hadden. Hierbij werd de lengte van de sequentie niet genoemd. Proefpersonen werd gevraagd om deze volgorde of delen ervan te tekenen. In de delen C en D van de vragenlijst kregen proefpersonen tekeningen van (delen van) de sequenties te zien die in de studies werden gebruikt. Proefpersonen moesten aangeven of ze (delen van) de sequentie uitgevoerd hadden en hoe zeker ze hier van waren.

De resultaten van alle studies lieten zien dat herkenning van de volgorde varieerde tussen proefpersonen, terwijl de uitvoering altijd verbeterde. Dit geeft aan dat expliciete kennis zich niet altijd ontwikkelt met sequenties van gerichte bewegingen, terwijl impliciete kennis zich wel altijd ontwikkelt.

Conclusies

De vijf empirische studies in deze dissertatie zijn uitgevoerd om mechanismen die ten grondslag liggen aan impliciet en expliciet sequentieleren bij gericht bewegingen te doorgronden. In het begin waren we er niet zeker van of impliciete en expliciete sequentiekennis zich op dezelfde manier zou ontwikkelen als in de toetsdruk-versie van de seriële RT taak. Eén belangrijke conclusie van het onderzoek in deze dissertatie is dat alle proefpersonen sneller waren wanneer ze herhaaldelijk doelen in een vaste volgorde aan moesten raken. Bovendien toonden de resultaten aan dat een substantieel deel van de proefpersonen zich bewust was van de volgorde waarin ze de doelen aanraakten, terwijl andere proefpersonen geen idee hadden van de volgorde waarin ze de doelen aanraakten. Eerstgenoemden ontwikkelden daarom expliciete sequentiekennis en laatstgenoemden ontwikkelden alleen maar impliciete sequentiekennis aangezien ze wel sneller waren. Deze resultaten met gerichte bewegingen komen overeen met de resultaten van de toetsdruk-versie van de seriële RT taak.

We waren vooral geïnteresseerd in mogelijke interferentie tussen de aansturing van sequenties en aansturing van de individuele gerichte bewegingen. Daarom stelden we drie hypothesen voor in Hoofdstuk 2. Deze interferentie kan niet worden onderzocht met toetsdrukken, maar we verwachtten belangrijke informatie te kunnen vinden over de processen die betrokken zijn bij het ordenen en uitvoeren van bewegingen. De drie hypothesen verschilden in het feit of interferentie optreedt tussen aansturing op het sequentiële niveau (d.w.z. het selecteren van ieder volgend element) en aansturing van individueel gerichte bewegingen. Wanneer deze processen niet interfereren kunnen deze processen samenvallen. In dit geval is er minder noodzaak om sequentiële aansturing gedurende het zogenaamde "response to stimulus interval" (RSI) uit te voeren dan wanneer deze processen serieel uitgevoerd moeten worden. Deze hypothesen werden getest door de grootte van het doel en het RSI te manipuleren. Hierbij namen we aan dat de ontwikkeling en toepassing van sequentiële kennis min of meer gevoelig was voor het verlengen van het RSI bij verschillende doelgroottes. Bovendien waren we er in geïnteresseerd of deze resultaten zouden verschillen voor proefpersonen die zich wel danwel niet bewust waren van de volgorde. Dit zou namelijk aan kunnen geven dat interferentie tussen gerichte bewegingen en sequenties verschillend is voor impliciete en expliciete kennis.

De resultaten van de testfasen van de experimenten in de Hoofdstukken 2 en 3 stemmen overeen, omdat ze laten zien dat bewuste proefpersonen voordeel hebben van een langer RSI. Dit komt overeen met de hypothese dat deze proefpersonen het RSI nodig hadden om hun expliciete sequentiekennis toe te passen en dit niet konden gedurende de uitvoering van de voorafgaande gerichte beweging. Daarom ondersteunen de resultaten van de Hoofdstukken 2 en 3 de hypothese dat toepassing van expliciete sequentiekennis interfereert met de uitvoering van gerichte bewegingen.

Wat betreft de onbewuste proefpersonen, lieten de twee experimenten in Hoofdstuk 2 zien dat, ongeacht de grootte van het doel, sequentiekennis al werd toegepast wanneer het RSI 0 ms was, en dat dit niet verbeterde met een langer RSI. Dit geeft aan dat impliciete sequentiekennis toegepast kan worden gedurende de voorafgaande beweging en ondersteunt de hypothese die aanneemt dat er geen interferentie is tussen aansturing van de volgorde van de elementen en van uitvoering van gerichte bewegingen. De resultaten van Hoofdstuk 3 lieten echter zien dat onbewuste proefpersonen voordeel hebben van een langer RSI, wat het idee steunt dat sequentiekennis niet geheel wordt toegepast gedurende de uitvoering van een gerichte beweging. Mogelijke verklaringen voor dit verschil tussen de Hoofdstukken 2 en 3 zijn dat onbewuste proefpersonen ook een beetje expliciete kennis hebben (welke alleen werd toegepast nadat een beweging geëindigd was), of een kleiner aantal doelgebieden in Hoofdstuk 3 (en als gevolg hiervan meer mogelijkheden met betrekking tot volgende bewegingen). Bovendien zou impliciete kennis meer voordeel kunnen hebben van de grotere doelen die in Hoofdstuk 2 gebruikt werden.

Deze resultaten geven aan dat het verwerken van expliciete sequentiekennis interfereert met het uitvoeren van bewegingen naar kleine en grote doelen. De resultaten zijn echter dubbelzinnig wanneer het gaat om het feit of het verwerken van impliciete sequentiekennis interfereert met de aansturing van gerichte bewegingen. Het is belangrijk dat sequentiekennis zich ontwikkelde bij zowel bewuste als onbewuste proefpersonen, ongeacht de grootte van de doelen. Dit suggereert dat, in tegenstelling tot de toepassing van impliciete en expliciete kennis, de ontwikkeling van impliciete en expliciete sequentiekennis niet wordt belemmerd door het uitvoeren van gerichte bewegingen.

De resultaten van het tweede experiment in Hoofdstuk 2 suggereren ook dat de grootte van de doelen de toepassing van expliciete sequentiekennis beïnvloedt. Bij de kleinere doelen lieten de resultaten geen interferentie zien van het verwerken van expliciete sequentiekennis met de aansturing van gerichte bewegingen. Het lijkt er op dat de langere duur van bewegingen naar de kleinere doelen gebruikt wordt voor het toepassen van sequentiekennis. De resultaten met grotere doelen lieten echter zien dat bewuste proefpersonen hun expliciete sequentiekennis zelfs niet toe konden passen bij een RSI van 400 ms. Deze data laten zien dat bewuste proefpersonen moeten leren hoe ze hun expliciete sequentiekennis toe moeten passen gedurende het RSI.

Een tweede kwestie in deze dissertatie is de transfer van impliciete en expliciete sequentiekennis naar verscheidene situaties. We hebben ons allereerst gericht op een indicatie in Hoofdstuk 2 dat onbewuste proefpersonen hun hand mogelijk bewogen naar een centrale positie, iedere keer nadat ze een doel uit de sequentie geraakt hadden. Dit is een logische strategie wanneer je niet weet naar welk doel de volgende beweging toe gaat. Maar het suggereert tevens dat het bewegen naar deze centrale positie de ontwikkeling van (op zijn minst) impliciete sequentiekennis niet belemmert. We onderzochten dit idee in Hoofdstuk 4, door voor één groep proefpersonen een centraal doel toe te voegen. De proefpersonen moesten dit centrale doel iedere keer aanraken, nadat ze een doel uit de sequentie aangeraakt hadden. De resultaten bevestigden dat niet alleen impliciete, maar ook expliciete sequentiekennis zich ontwikkelden, ondanks de noodzaak om steeds naar dit centrale doel te bewegen. Toch bleek in de testfase dat het toevoegen of weglaten van het centrale doel transfer belemmerde. De enige uitzondering hierop was wanneer het centrale doel uit de oefenfase in de testfase werd weggelaten bij onbewuste proefpersonen. Dit kan makkelijk verklaard worden door het idee dat het weglaten van het centrale doel de taak voor deze proefpersonen niet wezenlijk veranderde: Net als in Hoofdstuk 2 bewogen ze hun hand waarschijnlijk nog steeds naar de centrale positie, ondanks het weglaten van het centrale doel. Deze resultaten geven aan dat de beweging naar een centraal doel opgenomen kan worden in impliciete en expliciete sequentierepresentaties, zonder sequentieleren te beïnvloeden. Deze bewegingen lijken een belangrijk deel van de representatie te zijn, aangezien het weglaten of toevoegen van de noodzaak om naar een centraal doel te bewegen het nut van de ontwikkelde sequentierepresentatie beïnvloedt. Dit wordt mogelijk veroorzaakt door de noodzaak om bewust het automatische bewegingspatroon te veranderen.

Om de schema theorie van Schmidt (1975) voor de toepassing van impliciete en expliciete sequentiekennis te onderzoeken, manipuleerden we in Hoofdstuk 5 de absolute en relatieve diameters van doelen en afstanden tussen doelen. De resultaten bevestigden de wet van Fitts: bewegingstijden veranderden niet wanneer absolute groottes werden gewijzigd, zo lang werd voldaan aan de wet van Fitts (zie Fitts, 1954). Belangrijker nog, de resultaten ondersteunden grotendeels het idee dat sequentiekennis toegepast kan worden naar situaties met een andere absolute grootte, maar met dezelfde relatieve ruimtelijke schikking. Dit suggereert dat de afstand van een beweging als een parameter ingesteld kan worden, zoals de schema theorie aanneemt. Slechts proefpersonen zonder expliciete kennis bleken slechter te presteren wanneer bewegingen meer precies waren (d.w.z. grotere "Indexes of

Difficulty”). De noodzaak om niet geoefende precieze bewegingen uit te voeren leek te interfereren met het toepassen van impliciete sequentiekennis.

Uit een onderzoek van Verwey en Clegg (2005) waarbij een toetsdruk-versie van de seriële RT taak werd gebruikt, bleek dat sequentiekennis overgedragen wordt naar gespiegelde sequenties. Daarom onderzochten we in Hoofdstuk 6 of impliciete en/of expliciete sequentiekennis misschien zodanig is vormgegeven, dat de transfer naar een iets andere spatiële lay-out gemakkelijk is. In het bijzonder onderzochten we de transfer naar een geroteerde en een puntgespiegelde versie van de sequentie. Zulke veranderingen zijn duidelijk mogelijk met de huidige 2-dimensionale stimulus en respons indelingen en niet met de 1-dimensionale indelingen die kenmerkend zijn voor de toetsdruk-versie van de seriële RT taak. In tegenstelling tot de resultaten van Verwey en Clegg (2005), gaven de resultaten van dit hoofdstuk aan dat er geen transfer was naar de veranderde lay-outs. Dit weerlegt voor de gerichte beweging-versie van de seriële RT taak het idee dat impliciete of expliciete sequentiekennis wordt vastgelegd in een representatie, die ook gebruikt kan worden voor veranderde spatiële lay-outs.

De algehele conclusie is dat de resultaten die in deze dissertatie vermeld worden met elkaar overeenstemmen over het feit dat de ontwikkeling van impliciete en expliciete sequentiekennis erg lijkt op de sequentiekennis die gevonden wordt bij toetsdruk-bewegingen. Verder laten de resultaten bij het uitvoeren van gerichte bewegingssequenties zien dat 1) er substantiële interferentie is tussen de toepassing van expliciete sequentiekennis en de aansturing van gerichte bewegingen, 2) er enige taakafhankelijke interferentie is tussen de toepassing van impliciete sequentiekennis en de aansturing van gerichte bewegingen, en 3) de ontwikkeling van impliciete en expliciete sequentiekennis niet belemmerd wordt door de noodzaak om tevens gerichte bewegingen aan te sturen, onafhankelijk van de precisie ervan, hoewel toepassing van expliciete kennis geleerd moet worden. Bovendien 4) de noodzaak om naar een centraal doel te bewegen iedere keer nadat een regulier doel geraakt is beïnvloedt niet het vermogen om impliciete en expliciete sequentiekennis te ontwikkelen. De bewegingen naar dit centrale doel vormen echter een belangrijk deel van de representatie van de sequentie, en het weglaten of toevoegen van de noodzaak om naar een centraal doel te bewegen vermindert de bruikbaarheid van de ontwikkelde representatie van de sequentie. 5) Het idee dat impliciete en expliciete sequentiekennis gebruikt kunnen worden in grotere en kleinere spatiële lay-outs, zoals gesuggereerd wordt door de schema theorie, werd grotendeels bevestigd. Alleen wanneer bewegingen preciezer waren kan de toepassing van impliciete sequentiekennis verstoord worden. Tenslotte, 6) in tegenstelling tot suggesties met een toetsdruk-versie van de seriële RT taak, kunnen impliciete en expliciete sequentiekennis niet toegepast worden wanneer de 2-dimensionale lay-out van de gerichte beweging-versie van de seriële RT taak veranderd wordt.

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