

THE IMPORTANCE OF STIMULUS-RESPONSE
RULES IN SEQUENCE LEARNING

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THE IMPORTANCE OF STIMULUS-RESPONSE
RULES IN SEQUENCE LEARNING

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SUMMARY

For nearly two decades researchers have been interested in identifying what specifically is learned when individuals learn a sequence (e.g., sequence of stimuli, sequence of motor movements, etc.). Despite extensive research in the area, considerable controversy remains surrounding the locus of learning. There are three main theories concerning the nature of spatial sequence learning: sequence learning is purely perceptual, sequence learning includes a motor component and sequence learning is based on stimulus-response (S-R) rules. The present studies sought to disentangle these theories by demonstrating that sequence learning has both a perceptual and motor component and that altering S-R rules alone disrupts sequence learning. Experiment 1 results fully supported this S-R rule theory of sequence learning. Experiment 2 results provided only partial support for this theory, though the data were also inconsistent with both of the other accounts.

CHAPTER 1: INTRODUCTION

Learning spatial sequences (e.g., parallel parking a car, playing the piano, dancing the Argentinean Tango) is an essential part of our lives. Perhaps unsurprisingly, the study of sequence learning has been of considerable interest to cognitive psychologists for the last four decades. Despite the abundance of research in the area, fundamental questions about the cognitive processes involved still remain. One such question asks what is actually learned during implicit sequence learning. The present studies sought to demonstrate that when learning a spatial sequence, individuals learn a series of stimulus-response (S-R) rules.

Over five decades ago Karl Lashley (Lashley, 1951) impressed the importance of serial order in behavior as well as the importance of understanding how behavioral sequences are produced. He believed that sequential organization is central to behavior and stated that series of actions are chunked and responses are internally activated before being externally generated. He further believed that the activation itself does not contain the serial ordering of the actions, but rather there is an independent ordering system superimposed on the activation that selects a response. Lashley's novel ideas concerning the organization of sequential behavior were paramount in spurring further research in the area; however, his ideas are only applicable to explicit memory tests (Houghton & Hartley, 1995) and a direct correspondence between his ideas and implicit sequence learning is not obvious. Still, Lashley's contributions to the field cannot be overlooked and the importance of serial order in behavior is still a topic of interest as people seek to better understand the fundamental nature of sequence learning.

1.1 The Serial Reaction (SRT) Task

Since its introduction, the serial reaction time (SRT) task has become the standard procedure for studying implicit spatial sequence learning (Nissen & Bullemer, 1987). In the SRT task, participants are presented with several (typically 3-6) possible target locations. At the start of a trial, a target appears in one of these locations. Although participants are not told that a pattern exists, the targets are, in fact, presented in a very specific sequenced order (typically 6-12 positions long) that repeats several times in a given block. Participants are encouraged to respond to the location of the target as quickly and accurately as possible by pressing a button. With practice, reaction times (RTs) improve considerably, presumably because performance is aided by knowledge of the sequence (Nissen & Bullemer, 1987).

An additional measure of sequence learning is the *transfer effect*. The transfer effect is a comparison of average RTs on a block of random trials inserted after several sequenced blocks and the mean RT from the surrounding sequenced blocks. If learning has occurred, RTs on the random block will be significantly slower than those of the surrounding sequenced blocks.

The SRT task provides a measure of whether or not sequence learning has occurred. However, the typical procedure provides very little information about *what* is learned. General theories concerning the nature of learning in the SRT task can be divided into three broad categories: sequence learning is purely perceptual (Clegg, 2005; A. Cohen, Ivry, & Keele, 1990; Grafton, Salidis, & Willingham, 2001; Howard, Mutter, & Howard, 1992; Keele, Jennings, Jones, Caulton, & Cohen, 1995; Mayr, 1996; Verwey & Clegg, 2005), sequence learning is not purely perceptual and includes a motor component (Bischoff-Grethe, Geodert, Willingham, & Grafton, 2004; Willingham, 1999; Willingham, Wells, Farrell, &

Stemwedel, 2000) and sequence learning is based on stimulus-response pairings (Deroost & Soetens, 2006; Schwarb & Schumacher, 2006; Willingham, Nissen, & Bullemer, 1989). In the following section these theories are specifically defined and supported empirically.

The “perceptual” account of sequence learning (Clegg, 2005; A. Cohen, Ivry, & Keele, 1990; Grafton, Salidis, & Willingham, 2001; Howard, Mutter, & Howard, 1992; Keele, Jennings, Jones, Caulton, & Cohen, 1995; Mayr, 1996; Verwey & Clegg, 2005) states that sequence learning is stimulus-based. What this means in terms of the SRT task is that participants learn, for example, that a target in position 2 followed by a target in position 3 is always followed by a target in position 1. Both what type of response is made and even whether a response is made at all are irrelevant because sequence learning will occur regardless of the response.

The response-based theory (Bischoff-Grethe, Geodert, Willingham, & Grafton, 2004; Willingham, 1999; Willingham, Wells, Farrell, & Stemwedel, 2000) proposes that sequence learning has a motor component and that both making a response and the response made are important when learning a sequence. In the SRT task, this means that participants learn that if they push the center button on trial 1 and the button directly to the right on trial 2, then they will press the button to the far left on trial 3. What is learned is the location of the response and the stimulus itself is of little importance.

Finally the theory that sequence learning results from the learning of S-R pairs (Deroost & Soetens, 2006; Willingham, Nissen, & Bullemer, 1989) implicates a perceptual and a motor component that are both necessary for learning a sequence. This account states that in the SRT task, it is not the sequence of stimuli that is learned nor is it the sequence of

responses, but rather the combined stimulus and response sequence. Substantial support has been reported for each of these three theories.

1.2 Sequence Learning is Perceptual

There is considerable support for the idea that sequence learning is stimulus-based and purely perceptual (Clegg, 2005; A. Cohen, Ivry, & Keele, 1990; Grafton, Salidis, & Willingham, 2001; Howard, Mutter, & Howard, 1992; Keele, Jennings, Jones, Caulton, & Cohen, 1995; Mayr, 1996; Verwey & Clegg, 2005). This research suggests that a sequence is learned via the formation of stimulus-stimulus associations (relationships between the stimuli) and is not dependent on response (A. Cohen, Ivry, & Keele, 1990; Curran, 1997). Cohen, Ivry, and Keele (1990, Experiment 2) were the first to demonstrate the sequence learning is effector-independent. They trained participants on a sequence in the SRT task requiring participants to respond using four fingers of their right hand. After ten training blocks, they provided new instructions requiring participants respond with their right index finger only. On each trial, a secondary tone-counting task was performed simultaneously. Participants demonstrated unimpaired sequence learning after switching effectors when compared to a control group that also switched effectors, but only saw random trials after the switch was made. These data suggest that sequence knowledge is dependent on the sequence of stimuli rather than on the sequence of motor responses and that sequence learning is independent of the motor system that implemented the movement.

Verwey & Clegg (2005) further investigated the issue of perceptual learning and effector-independence considering the possibility that motor coding develops slowly (Hikosaka et al., 1999) and that the motor system may play a role late in learning. They trained participants instructed to respond with three fingers of one hand on over 1,300

repetitions of the sequence (typical SRT studies only include 50-100 sequence repetitions). They then tested participants' knowledge of the sequence with both the practiced hand and the unpracticed hand. Data revealed that participants responded to sequenced trials more quickly with the practiced hand compared to the unpracticed hand; based on these results, the authors concluded that late learning is effector-dependent.

These data seem to contradict the perceptual theory of sequence learning. However, there are many differences (e.g., number of sequence repetitions and degree of awareness of the sequence) between this study and other sequence learning studies. It is interesting to note is that when using the unpracticed hand, RTs were faster for the practiced sequence than for a new sequence indicating that there is still some effector-independence in later learning. These results suggest that although a motor component may become important late in learning, the previously reported non-motor or perceptual component (A. Cohen, Ivry, & Keele, 1990; Keele, Jennings, Jones, Caulton, & Cohen, 1995) is present at all stages of sequence learning.

Howard, Mutter, and Howard (1992) provided additional support for the non-motoric theory of sequence learning. In order to directly test the issue of perceptual versus motor sequence learning they trained two groups of participants on a sequence: One group responded with button-pushes to the location of the targets (Response group), the other group simply watched the targets shift locations (Observation group). After three blocks of training, all participants were asked to respond to the location of the targets with button-pushes. At test, both groups demonstrated significant transfer effects indicating that learning was significant and similar for both groups of participants. Howard and colleagues reported that sequence learning is purely perceptual because the sequence was learned even when no

response was made. However, in a follow-up explicit learning questionnaire, the Observation group was able to recall significantly more of the sequence than the Response group. It is possible that the Observation group relied on explicit knowledge of the sequence to perform at test (Willingham, 1999). We will return to this issue in the next section.

Clegg (2005, Experiment 2) further supported the theory that sequence learning is purely perceptual. He designed an SRT-like experiment in which there were four possible sequence locations and only two possible responses. Participants responded to the left two target locations with a left button-push and the right two target locations with a right button-push. After twelve training blocks, four test blocks were introduced in which portions of the learned sequence were occasionally altered so that the target appeared in a location inconsistent with the learned sequence (unexpected location). Results demonstrated that RTs were slower for targets that appeared in an unexpected location compared to when they appeared in the expected location. This was true even for unexpected locations that required the same response as the expected location. Clegg concluded that sequence learning in the SRT paradigm is facilitated by stimulus-based representations and that such learning is not motoric.

Additional support for the idea that sequence learning is perceptual can be found outside of the SRT task literature. Grafton, Salidis, and Willingham (2001, Experiment 2a), for example, trained participants on a visually-guided tracking task in which participants used a joystick to follow a moving target that traveled back and forth horizontally across the screen either in a sequenced or unsequenced pattern. During training, the joystick was reversed so that a leftward movement shifted the cursor to the right. At test, the joystick was standard (right movement shifted cursor to the right) and either the target movement

(Perceptual group), the hand movement (Motor group) or the entire experiment (Identical group; joystick was always reversed) was kept constant. During the testing phase, the Motor group showed no evidence of sequence knowledge. The Perceptual and Identical groups, however, both showed significant sequence learning at test. Thus sequence knowledge transferred from training to test only when the pattern of stimuli was maintained.

In an attempt to explicitly distinguish stimulus-based learning from response-based learning, Mayer (1996) conducted an experiment in which objects appeared at either four spatial locations without secondary-task distraction (Experiment 1) or three spatial locations with a tone-counting secondary task (Experiment 2). The object presentation order as well as the spatial presentation order was sequenced (different sequences of differing lengths were used for each). What makes this experiment particularly interesting is that participants responded to the *identity* of the object and not the *location* of the object. In both experiments, RTs were slower (indicating that learning had occurred) both when only the object sequence was randomized and when only the spatial sequence was randomized. Mayer provided compelling support for the perceptual nature of sequence learning by demonstrating that the spatial sequence was learned despite the fact that responses were made to an unrelated aspect of the experiment (object identity).

Together these studies provide support for the idea that sequence learning is effector-independent (A. Cohen, Ivry, & Keele, 1990; Keele, Jennings, Jones, Caulton, & Cohen, 1995; Verwey & Clegg, 2005), non-motoric (Grafton, Salidis, & Willingham, 2001; Mayr, 1996) and purely perceptual (Clegg, 2005; Howard, Mutter, & Howard, 1992). These studies suggest that sequence learning is stimulus-based and dependent on the formation of stimulus-stimulus contingencies (Curran, 1997). However, there are a number of studies that refute

such claims and support the theory that sequence learning is not purely perceptual, is motoric, and is dependent on response-response contingencies (e.g., Bischoff-Grethe, Geodert, Willingham, & Grafton, 2004; Willingham, 1999; Willingham, Wells, Farrell, & Stemwedel, 2000).

1.3 Sequence Learning is Not Purely Perceptual

We have seen that there are a number of studies that provide support for the perceptual nature of sequence learning, however, there is equally compelling support for the non-perceptual nature of sequence learning. It is thus apparent that the question of what is learned during sequence learning tasks is far from obvious.

Willingham (1999, Experiment 1) hypothesized that the results of the Howard, Mutter, and Howard (1992) experiment were a product of the large number of participants who learned the sequence explicitly and that if those participants were removed from the analysis, the data would be quite different. Willingham thus replicated the Howard study in which some participants simply watched the sequence of stimuli for several blocks without making a response and only at the end of the experiment began responding (Observation group) while other participants responded to the location of the target throughout the whole experiment (Response group). Data from the Observation group were analyzed both including and excluding participants with explicit knowledge of the sequence. When those individuals with explicit knowledge were included, the results replicated the Howard, Mutter, and Howard results; both the Observation group and the Response group learned the sequence. However, when only those participants without explicit knowledge were considered, only the Response group showed a significant transfer effect indicating a benefit

of sequence learning. Willingham concluded that when explicit knowledge of the sequence is low, knowledge of the sequence is contingent on the sequence of motor responses.

In an additional experiment, Willingham (1999; Experiment 3) provided further support for this theory. Using the SRT task, he trained participants on a sequence and instructed them to make incompatible manual responses to the targets. This incompatible mapping required participants to respond to a target with the finger one position to the right of the target location (Figure 1a). Participants used this incompatible mapping for three blocks (training phase) and then switched to using a compatible mapping in which the finger directly below the target was used to make the response (testing phase). Participants were divided into three groups: The Control group always responded using the compatible mapping and the two experimental groups were trained using the incompatible mapping and then switched to compatible mapping at test. The two experimental groups were the Motor group in which the sequence of button-presses was maintained after transferring to the compatible mapping and the Perceptual group in which the sequence of visual stimuli presentation was maintained during the testing phase. Sequence knowledge was tested both during the training and the testing phases of the experiment. During the training phase, all three groups showed a significant transfer effect whereas during the testing phase, the transfer effect was significant only for the Control and Motor groups (Figure 1b). Willingham (1999) concluded that learning cannot be purely perceptual and that there must be some motor component because maintaining the perceptual sequence from training to test did not facilitate sequence learning while maintaining the motor sequence did. He proposed that what is learned in the SRT task is the sequence of response locations.

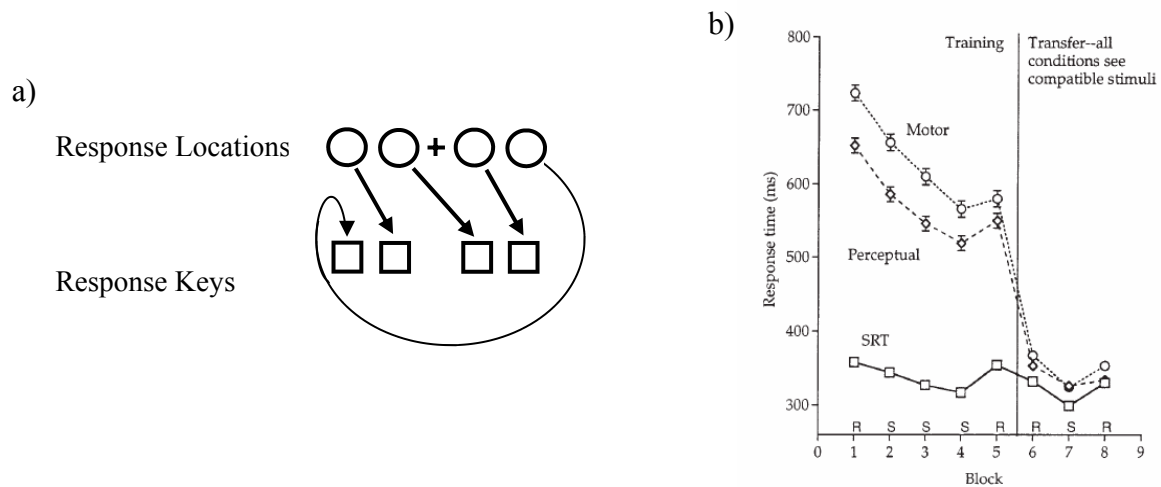


Figure 1. Willingham (1999) Experiment 3

a) Incompatible response mapping. b) Mean RTs across block separated by group. Error bars are standard errors calculated within subjects. The absence of error bars indicates that they were too narrow to be printed. The increase in RTs between blocks 4 and 5 is the transfer effect during the training phase. The increase in RTs between blocks 7 and 8 is the transfer effect during the test phase. At test the Perceptual group did not show significant transfer block effect.

These results were replicated in an fMRI study examining response-based sequence learning from a neurological perspective (Bischoff-Grethe, Geodert, Willingham, & Grafton, 2004). Though certain aspects of the procedure were modified (e.g., block length, block order, number of blocks, etc.) to be compatible with fMRI imaging, the results were the same. Participants began by using an incompatible mapping and then switched to using a compatible mapping after several blocks of sequenced trials (as in Willingham, 1999). There were two groups of participants: A Motor group and a Perceptual group (as defined in Willingham, 1999). Based on a free-generation task completed at the end of the experiment, participants were divided into a high and a low recall and these groups were analyzed separately. The purpose of this division was to sort out participants who could explicitly describe the sequence after the experiment from those who could not. When the sequence could not be recalled, results were identical to the Willingham (1999; Experiment 3) results

in that there was a significant transfer effect for the Motor, but not the Perceptual group. Conversely, when the sequence could be recalled, there was no significant transfer effect for either group. Based on these behavioral data Bischoff-Grethe and colleagues concluded that sequence learning is response-based unless participants can explicitly recall the sequence. No explanation was provided for why explicit knowledge of the sequence impairs motor learning. Imaging results demonstrated that this response-based learning recruits premotor and supplementary motor areas as well as the inferior parietal cortex.

Willingham, Wells, Farrell, and Stemwedel (2000; Experiment 2) conducted a similar study investigating the motoric nature of sequence learning. They trained participants on a sequence requiring a different incompatible mapping than was previously used (Willingham, 1999). This incompatible mapping required participants to cross their left and right hands and then responded with the finger directly below the target location. After five blocks of training trials, participants uncrossed their hands and continued to respond by pressing the button directly below the target location. There were four groups: Two control group and two experimental groups. The experimental groups were the Locations group in which neither the sequence of perceptual stimuli nor the location of response changed despite the new mapping; and the Fingers group in which the series of perceptual stimuli and the response locations changed, but the series of finger movements remained the same. The two control groups were the Random group who used the same mappings as the experimental groups, but never saw sequenced stimuli and the Both group in which participants always responded with uncrossed hands. Participants in the Locations and the Both groups showed significant benefit of sequence learning during the testing phase, whereas the participants in the Random and Fingers groups did not. Willingham and colleagues thus concluded that in

the SRT task, participants learn the series of response locations. These results support Willingham's (1999) earlier claim that learning is not purely perceptual and that there is a motoric component to sequence learning; not in the sense of muscle movements, but rather selecting targets for motor movement.

Taken together these studies provide support for the idea that sequence learning has a motor component and is not purely perceptual (Bischoff-Grethe, Geodert, Willingham, & Grafton, 2004; Willingham, 1999; Willingham, Wells, Farrell, & Stemwedel, 2000).

However, we have already seen substantial support for the idea that sequence learning is perceptual (Clegg, 2005; A. Cohen, Ivry, & Keele, 1990; Grafton, Salidis, & Willingham, 2001; Howard, Mutter, & Howard, 1992; Keele, Jennings, Jones, Caulton, & Cohen, 1995; Mayr, 1996; Verwey & Clegg, 2005).

Willingham and colleagues (1999, 2000) posited a number of different reasons that could explain why their results are in stark contrast with the perceptual theory of sequence learning. They suggested that explicit sequence knowledge alters performance in the SRT task and that explicit knowledge could be driving the findings of many of those studies that report purely perceptual sequence learning. Evidence for this possibility lies in their replication (Willingham, 1999; Experiment 1) of the Howard, Mutter, and Howard (1992) study in which they found support for the response-based theory (contrary to the Howard, Mutter, and Howard findings) after removing all explicit learners from the analysis. They also suggested that it is possible that the stimulus locations in the studies that support the perceptual theory were arranged at such a distance that participants moved their eyes from location to location (e.g. Mayer, 1996). Eye movements could be considered a type of

response (Willingham, 1999) and it is possible that participants learned the sequence of eye movements and not the stimulus-stimulus contingencies.

The issue of what is learned in sequence learning has yet to be resolved. Willingham (1999) observed that limited power in various studies could be a reason that results are so diverse. He further stated that a lot of power is required to conclude that an effect is absent and with limited power it is difficult to make claims about individual perceptual and motor components; however, limited power still allows researchers to determine that neither alone can support sequence learning. Given that if there is support for both a perceptual and motoric component to sequence learning, it is possible that what is actually learned is a combination of both the perceptual stimulus and the motor response.

1.4 Sequence Learning is Based on S-R Rules

The present studies sought to demonstrate that the learning of S-R rules is of particular importance to sequence learning, thus emphasizing the significance of both perceptual and motor components. It is important to note the present hypothesis is that S-R rules and not merely individual S-R associations are essential for learning a sequence. Here S-R associations are as defined by Willingham and colleagues (1999, 2000): Very specific stimuli (e.g., a shaded circle or a digit) are paired only with very specific responses (e.g., a particular key). This clarification is consistent with previous data that have suggested that “response selection involves use of rule systems rather than individual S-R associations” (Duncan, 1977). Duncan demonstrated that S-R mappings are governed by systems of rules and not individual S-R associations. Furthermore, he concluded that these systems of rules could be applied to numerous S-R associations. Thus, in a four position compatible mapping task in which participants respond with the button positioned directly below the target

location (e.g., Bischoff-Grethe, Geodert, Willingham, & Grafton, 2004; Olson et al., 2006; Willingham, 1999; Willingham, Wells, Farrell, & Stemwedel, 2000) one S-R rule could describe all four S-R associations.

In the earliest attempt to determine what is learned in the SRT task, Willingham, Nissen, and Bullemer (1989) emphasized the importance of S-R pairings during sequence learning and provided support for idea that sequences are represented in series of S-R bonds. Willingham, Nissen, and Bullemer (1989, Experiment 3) asked participants to respond to the color of an X that appeared at one of four locations. The X could be one of four colors that were each mapped to a separate response-button; participants were trained in a previous session to ensure that they were competent with the color mapping. Participants were randomly assigned to three groups: the Control group in which both the sequence of colors and sequence of target locations were random, the Perceptual group in which the sequence of colors was random, but the target locations were sequenced, and the Response Sequence group in which the sequence of target locations was random, but the color of the X's were sequenced. After four blocks of responding to the *color* of the X's (training phase), the participants switched to a new task (testing phase). During the five testing phase blocks, all X's were white and participants responded to the *location* of the targets (standard SRT task); the targets followed the same spatial sequence as during the training phase.

Results revealed no benefit of sequence learning for the Perceptual group during the training phase, while the Response Sequence group did demonstrate a benefit. After switching to standard SRT task, all groups showed the same amount of sequence learning and the Response Sequence group showed no benefit of previously learning the sequence. Willingham and colleagues concluded that response selection is important and that sequence

learning is neither stimulus-based nor motor-based, but rather the result of condition-action pairs or S-R bonds. Because the S-R rules (respond to color vs. respond to location) were changed from training to test, during the testing phase there was no benefit of having learned the sequence during training phase.

It is important to notice that Willingham, Nissen and Bullemer (1989) design is very similar to that used by Mayr (1996) in which he concluded that sequence learning was purely perceptual. Mayr explained that the experimental design of Willingham, Nissen and Bullemer may have obscured the perceptual component. Mayr suggested that the stimuli were too close together that the stimuli colors were highly distinct in the original study. Due to the proximity and salience of the stimuli, it is feasible that predicting the location of an upcoming stimulus produced only small performance benefits and that is why a perceptual component was not identified.

Willingham (1999) reported that the results of his Experiment 3 were inconsistent with his earlier claim that S-R bonds facilitate sequence learning (Willingham, Nissen, & Bullemer, 1989). Namely when participants switched from incompatible to compatible mapping in his 1999 study, S-R pairings were changed but sequence learning was not disrupted. However, this statement is only true if the S-R component of sequence learning is conceptualized as highly specific stimuli paired with highly specific responses (S-R associations). The proposed S-R rule explanation provides a different interpretation of the results. The compatible mapping in Willingham's Experiment 3 required participants to respond to a target location with the button directly below that location while the incompatible mapping required participants to respond to a target location with the button one position to the right of the location (Figure 1a). It is conceivable that participants'

performance on the two mappings was not contingent on two sets of S-R rules, but rather a simple transformation of the originally learned S-R rules.

It is interesting to note that Willingham has spent over a decade investigating the foundation of sequence learning and over time his view has been altered and refined. New experimental designs and new data have led him to reject his earlier interpretations in favor of different and more precise explanations. It is for this reason that his results and interpretations of these results over the years have provided support for all three theories concerning the nature of sequence learning (stimulus-based, response-based and S-R rule-based). Whereas early on he was a proponent of the role of S-R pairings in sequence learning, more recently he has advocated the role of response location as being fundamental for sequence learning.

Since the theory's introduction (Willingham, Nissen, & Bullemer, 1989), the idea that S-R pairs are important for sequence learning has seemingly fallen out of favor. Recently, however, researchers have begun to take a renewed interest in the role of S-R rules in sequence learning. Deroost and Soetens (2006) demonstrated that incompatible S-R mappings result in better sequence learning than compatible S-R mappings when task difficulty effects are controlled (via stimulus degradation) and that perceptual and response-based learning are unaffected. They concluded that the process of response selection is important for sequence learning and that incompatible S-R mappings require more controlled response selection which facilitates better learning.

Still further evidence of the importance of S-R rules in sequence learning comes from the results of my first year project (Schwarb & Schumacher, 2006) where the role of dual-task processing overlap in the sequence learning was investigated. All participants

completed the basic SRT task (Nissen & Bullemer, 1987) in which they responded to the spatial location of a target by pressing the button directly below that location (compatible mapping). A transfer block was inserted on the second to last block to test sequence knowledge. Participants were randomly assigned to three groups: A Single-Task group who completed the SRT task alone, a Dual-Task 0 ms SOA group who performed both the SRT task and a tone-identification task simultaneously, and a Dual-Task 750 ms SOA group who performed both the SRT and tone-identification task; however, the visual stimuli preceded the tone stimuli by 750 ms on any given trial. In the tone-identification task, a high or a low pitch tone sounded on each trial and participants responded to the pitch of the tone by saying “high” or “low.” Responses were recorded for both tasks on each trial allowing us to look specifically at processing overlap.

Participants showed a significant advantage of sequence learning in both the Single-Task and the Dual-Task 750 ms SOA groups, but not the Dual-Task 0 ms SOA group. These data suggest that sequence learning is impaired in the dual-task situation only when processes overlap. Additionally, because the input (visual and auditory) and output (manual and vocal) modalities were different, we concluded that the central processing mechanism, namely response selection, was disrupted in dual-task sequence learning. As noted above, the idea that response selection plays an important role in learning a sequence has been previously demonstrated (Deroost & Soetens, 2006; Willingham, Nissen, & Bullemer, 1989) and the importance of response selection in sequence learning logically implicates the role of S-R rules (Duncan, 1977).

1.4.1 An S-R Rule Explanation of Willingham (1999; Experiment 3)

Close evaluation of Willingham's (1999) Experiment 3 data suggests that a number of conclusions were prematurely drawn and that Willingham's results can be reinterpreted from an S-R rule perspective. Results from this study demonstrated that when response mapping switched and the sequence of perceptual stimuli was changed so that the sequence of button-presses remained the same, participants showed a benefit of sequence learning (Motor group). However, when the response mapping was switched the sequence of perceptual stimuli remained the same but the sequence of button-presses was altered, participants showed no sequence learning (Perceptual group; Figure 1b); though, in truth, there was a trend toward significance ($p < 0.10$)

Careful analysis of the data reveals a number of potential confounds. An initial concern is that during the training phase, in which both groups performed identical tasks, there were group differences. First, participants in the Perceptual group were considerably faster than those in the Motor group. Although the analysis is not reported in the paper, the Perceptual group responds approximately 60 ms faster than the Motor group, a difference far greater than the reach of the standard error bars. Group transfer effects in the training phase were not significantly different from each other; however the Perceptual and SRT groups transfer effects were significantly greater than zero whereas the Motor groups transfer effect was not. In the testing phase, the transfer effect was calculated by comparing RTs on the block 8 (random trials) to RTs on block 7 (sequence trials). Typically, the transfer effect is calculated by comparing the RTs from the block of interest (e.g., the sequenced block) to the average RTs from the surrounding two blocks (e.g., random blocks). Willingham (1999) reported that this procedure was not used during the testing phase because subjects were "still adjusting to the change in S-R mapping, as is clear, because Block 8 RTs are reliably faster

than Block 6 RTs,” however evidence for this claim is not obvious (Figure 1b). Although block 8 mean RTs are reliably faster than block 6 mean RTs, this difference seems to be driven by the Perceptual group alone. RTs on blocks 6 and 8 for the Motor group appear to be very similar. Also, if you compare the difference in RTs between blocks 4 and 5 for the Perceptual and Motor groups in the training phase (an insignificant difference considered theoretically uninteresting) it seems that the difference is larger than the difference in RTs between blocks 7 and 8 for the Perceptual and Motor groups in the testing phase (the theoretically interesting difference from which conclusions are drawn). Such confounds necessitate a reevaluation of Willingham’s interpretation.

1.5 Present State of the Literature

Taken together, it is evident that, despite considerable research in the area, there is little agreement concerning what is actually learned during sequence learning. Explanations are grouped into three distinct theories: one asserting that sequence learning is perceptual, another that sequence learning is the response-based, and still a third advocating the importance of S-R rules. Although the S-R hypothesis has lost favor over the past decade, recent research providing evidence for a response selection component to sequence learning (Deroost & Soetens, 2006; Schwarb & Schumacher, 2006) lends support to this theory. Further research is necessary to explicitly investigate the role of S-R rules in implicit sequence learning. Thus the present studies sought both to demonstrate the significance of S-R rules to learning a sequence and also to provide evidence that learning a spatial sequence is neither purely perceptual nor purely motoric but instead is contingent on learning a series of S-R rules.

CHAPTER 2: EXPERIMENT 1

2.1 Introduction

The purpose of Experiment 1 was to directly evaluate the three previously described theories of the cognitive processing involved in sequence learning. This was accomplished by demonstrating that changing the required S-R rules alone disrupts transfer of sequence knowledge and therefore sequence learning can neither be purely stimulus-based nor purely response-based. In order to investigate this issue, a modified version of Willingham's (1999) previously described Experiment 3 was conducted. In the present experiment, participants responded to a sequence of spatial positions with a button press indicating the location of the target on a given trial. During training, all participants responded using a complex set of S-R rules (Figure 2: indirect mapping). After the training phase, participants either continued to respond using the indirect S-R mapping (NoSwitch group) or switch to a mapping which required fewer S-R rules (Figure 2: direct mapping). Of those who switched to the direct S-R mapping, half of the participants saw the same sequence of visual stimuli but made a different sequence of button pushes (Perceptual group), while the other half saw a different sequence of visual stimuli, but maintained the same sequence of manual responses (Response group).

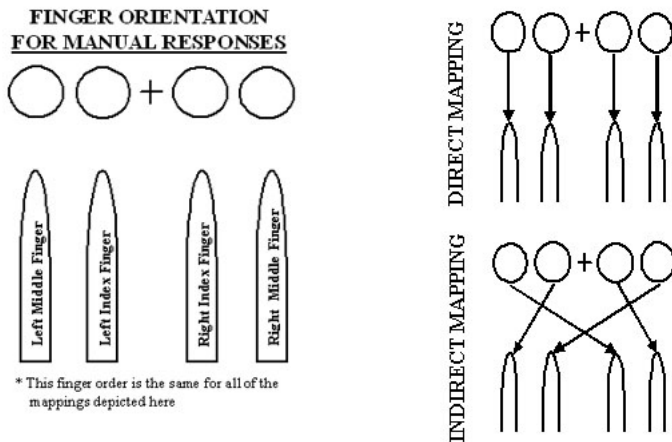


Figure 2. Experiment 1 Direct and Indirect S-R Mappings

The circles are the possible target locations and the arrows indicate which manual response should be used when a target appears in a given location.

Upon completion of the SRT task, participants completed two direct tests of sequence learning. The first included a series of questions concerning general knowledge of the sequence. After this test, participants were told that a repeating sequence was present throughout the experiment. They then completed a free-generation task in which they made up to 30 button pushes in an attempt to recreate as much of the sequence as possible. These measures were used only to evaluate general level of awareness.

It was hypothesized that when the S-R rules were maintained from training to test, participants would show a benefit of sequence knowledge during the testing phase; conversely, when only the stimulus sequence or only the response sequence was maintained throughout the experiment, there would be no benefit of sequence learning at test. Specifically it was predicted that knowledge of the sequence acquired during the training phase would transfer to the testing phase for the NoSwitch group and a significant transfer effect would be seen at test. Moreover, it was predicted that such sequence knowledge would *not* transfer for either the Perceptual or Response groups and no significant transfer effect would be present

at test. Thus it was expected that transfer of sequence knowledge would be disrupted regardless of which aspect of the sequence (perceptual or response) remained constant.

2.2 Method

2.2.1 Participants

Eighty-three participants from the Georgia Institute of Technology participated in this study in partial fulfillment of a course requirement. None of the participants were aware of the purpose of the study. Participants gave informed consent prior to beginning the experiment and all participants were treated in accordance with APA guidelines.

2.2.2 Stimuli and apparatus

Stimuli presentation and RT measurements were implemented using a Dell Dimension 3000 PC with a 17" monitor. All responses were recorded to the nearest millisecond. Manual responses were made on a Psychology Software Tools serial response box and participants viewed the visual display from a distance of approximately 60 cm.

2.2.3 SRT task

Four evenly spaced circles drawn with white lines on a black background were presented horizontally in the center of the computer monitor. The diameter of each circle subtended 3.5° of visual angle. Two circles were presented on either side of a white fixation cross; the fixation cross subtended $1.0^\circ \times 1.0^\circ$ of visual angle. The two innermost circles were positioned 3.0° on either side of the fixation cross and the outermost circles were positioned 3.5° from the outer edge of the inner circles. The entire horizontal display

subtended 28° of visual angle. On each trial, one of the circles filled in (white) and this shaded circle served as the target for that trial.

Participants were randomly assigned to the NoSwitch, Perceptual and Response groups. All participants performed 12 blocks of 96 trials each. Blocks 1-8 constituted the training phase and Blocks 9-12 constituted the testing phase (Table 1). Sequence learning in the training phase was measured behaviorally by comparing RTs from Block 7 to RTs from Block 8; during the testing phase, sequence learning was measured by comparing RTs from Block 11 to the average RT from Blocks 10 and 12. This was the transfer effect (Table 1).

Table 1. Block Design for Experiment 1

Block	1	2	3	4	5	6	7	8	9	10	11	12
Block Type	R	S	S	S	S	S	S	R	R	R	S	R
Sequence Type	S1	S2	S2	S2	S2	S2	S2	S3	S4	S5	S2	S6

Transfer Effect

2.2.4 The sequence

Six sequences were used in the SRT task. The sequences followed the statistical rules defined by Reed and Johnson (1994). The same sequence was used in the sequenced blocks (Blocks 2-7 and Block 11) and a different sequence matched for simple frequency information was used in each of the random blocks (Block 1, 8-10 and 12). Sequences were counterbalanced across participants.

2.2.5 Procedure

For all groups, the four circles and the fixation cross were presented on the screen at the start of each trial. This display remained on the screen for 2000ms before the start of the first trial. When a trial began, a target appeared in one of the four locations and remained on the screen for 100ms. Participants were instructed to respond to the targets as quickly and accurately as possible using their middle and index fingers of each hand. The circles and the fixation cross remained on the screen for the duration of the trial. The next trial began 250ms after a response had been made.

For all groups, Block 1 was an unsequenced¹ block, Blocks 2-7 were sequenced blocks, Blocks 8-10 were unsequenced blocks, Block 11 was a sequenced block and Block 12 was an unsequenced block (Table 1). As shown in Figure 2, when using the direct S-R mapping (Perceptual and Response groups; testing phase), participants respond to the circles from left to right with their left middle, left index, right index and right middle fingers respectively and when using the indirect S-R mapping (all groups; training phase. NoSwitch group; testing phase), participants respond to the circles from left to right with their right index, left middle, right middle and left index fingers respectively.

At the end of each block a screen was displayed informing participants of their accuracy as well as their mean RT for that block. At that time participants were also encouraged to respond as quickly and accurately as possible in the upcoming block.

Before the start of the experiment, participants completed four (NoSwitch group) or five (Perceptual and Response groups) practice blocks. These practice blocks were designed to familiarize participants with each mapping so that they would perform accurately during

¹ Unsequenced, here, does not mean without sequence, but rather not the sequence that was repeated on Blocks 2-8 and 11. These unsequenced blocks did, in fact, follow a sequence that was carefully matched for frequency information to the repeated sequence.

the experiment. These practice blocks were methodologically identical to the actual experimental blocks except that the target positions were always random and the blocks consisted of 40 trials each. Also, RT and accuracy feedback was given following each trial and at the end of each block. The NoSwitch group completed four blocks of trials using the indirect S-R mapping. The Perceptual and NoSwitch groups each completed one block of trials using the direct S-R mapping and four blocks of trials using the indirect S-R mapping.

After the experiment ended, all participants completed two direct tests of sequence learning. The first asked the following three questions (Frensch, Wenke, & Runger, 1999): What do you believe is the goal of this experiment? Did you notice that the shaded circles were presented in a certain sequence? Please describe whatever you noticed about the sequence. Regardless of their answers to the first set of questions, participants were asked complete a free-generation task. Before the free-generation task, participants were informed that the targets actually followed a repeating sequence and they were then asked to reproduce the sequence using up to 30 button-pushes. Their responses were echoed on the screen. They were then debriefed and issued credit.

2.3 Results and Discussion

2.3.1 Complete Data Set

2.3.1.1 Results

2.3.1.1.1 Excluded Participants

One participant from the NoSwitch group was removed from the analysis because his training phase learning score was more than three standard deviations below the mean.

2.3.1.1.2 Reaction Times: Training Phase Sequenced Blocks

Mean data were analyzed with a two-way analysis of variance (ANOVA) with a between-subjects variable for Group (NoSwitch, Perceptual, Response) and a within-subjects variable for Block (2-7). Mauchley's test of sphericity showed that the assumption of sphericity was violated for this analysis ($p < 0.001$), so the degrees of freedom were corrected according to the Huynh-Feldt adjustment. The ANOVA revealed a significant main effect of Block, $F(4.1, 320.2) = 61.21, p < 0.001$, and a significant Block x Group interaction, $F(8.1, 320.2) = 3.07, p < 0.01$. These data indicate that mean RTs decreased across blocks and that this decrease varied between groups. This interaction is likely driven by the fact that the Response group was approximately 100ms faster than the other two groups on Block 2 and all groups were equally as fast by Block 7. There was no significant main effect of Group, $F(2, 79) = 0.20, p = 0.82$. These data are plotted in Figure 3.

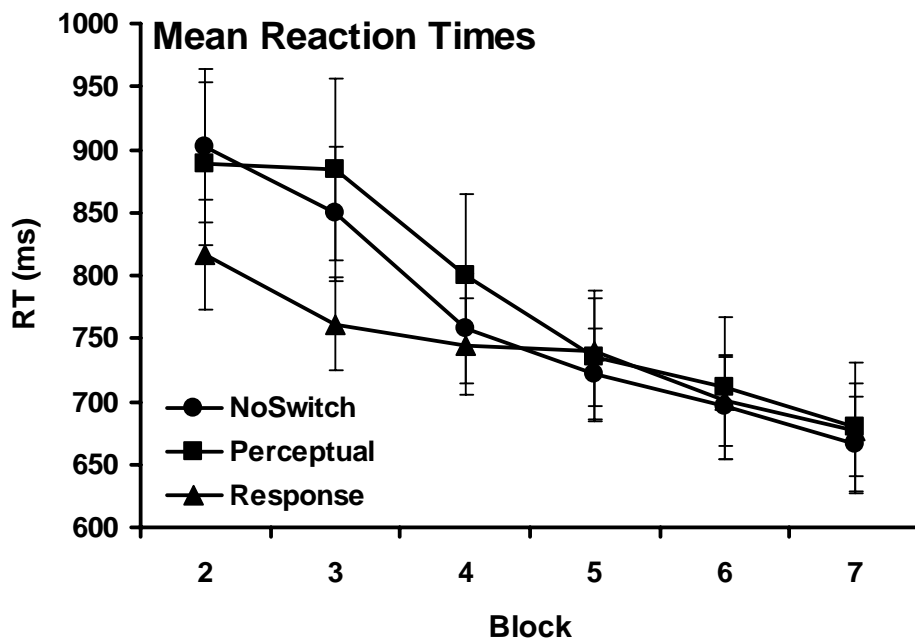


Figure 3. Training Phase Mean Reaction Times (Complete Data Set)
Mean RTs across sequenced Blocks 2-7 for all three groups.

2.3.1.1.3 Training Phase Transfer Effect

Change in RT on blocks 8 and 11 are theoretically interesting in this study as they provide a test for evaluating whether or not a benefit of sequence learning existed during the training and testing phases. If sequence learning occurred during the training phase we would expect the mean RT from Block 8 to be slower than the mean RT from Block 7. Because of the specificity of this transfer effect prediction, one-tailed comparisons were used in all tests of the transfer effect. As shown in Figure 4, mean RTs significantly increased after switching sequenced to unsequenced trials for the NoSwitch, $t(31) = 1.86, p < 0.05$, Perceptual, $t(23) = 2.15, p < 0.05$, and Response, $t(25) = 2.81, p < 0.01$, groups. These significant transfer effect results indicate that participants in all three groups were able to acquire knowledge of the sequence during the training phase.

A two-way repeated measures ANOVA with Structure (Sequenced, Unsequenced) as a within subjects variable and Group (NoSwitch, Perceptual, Response) as a between subject variable was conducted on the testing phase transfer data. The main effect of Structure, $F(1, 79) = 15.64, p < 0.001$, was statistically significant indicating that participants were faster on Block 9 than on Block 10. Neither the main effect of Group, $F(2, 79) = 0.09, p = 0.91$, nor the Structure x Group interaction, $F(2, 79) = 0.53, p = 0.59$, were significant. This means that there were no significant group differences in the training phase transfer effect.

2.3.1.1.4 Testing Phase Transfer Effect

Transfer effects were calculated in the testing phase by conducting a *t*-test on the mean RT from sequenced Block 11 and the average mean RTs from the surrounding unsequenced blocks (Block 10 and Block 12; Figure 4). A significant testing phase transfer effect would indicate that knowledge of the sequence transferred from the training phase to

the testing phase. The testing phase transfer effect was significant for the NoSwitch group, $t(31) = 3.27, p < 0.001$, and the transfer effect was not significant for either the Perceptual, $t(23) = -0.23, p = 0.41$, or the Response, $t(25) = 0.78, p = 0.22$, groups.

A two-way Structure by Group ANOVA was also performed on the testing phase transfer data. The main effects of both Structure, $F(1, 79) = 6.34, p < 0.05$, and Group, $F(2, 79) = 54.46, p < 0.001$, as well as the Structure x Group interaction, $F(2, 79) = 6.14, p < 0.01$, were significant. Post Hoc analysis of group differences revealed that the NoSwitch group was significantly different from both the Perceptual ($p < 0.001$) and Response ($p < 0.001$) groups. This is unsurprising because at test participants in the NoSwitch group used the indirect mapping and participants in the Perceptual and Response groups used the direct mapping. The Perceptual and Response groups were not significantly different from each other ($p = 0.99$).

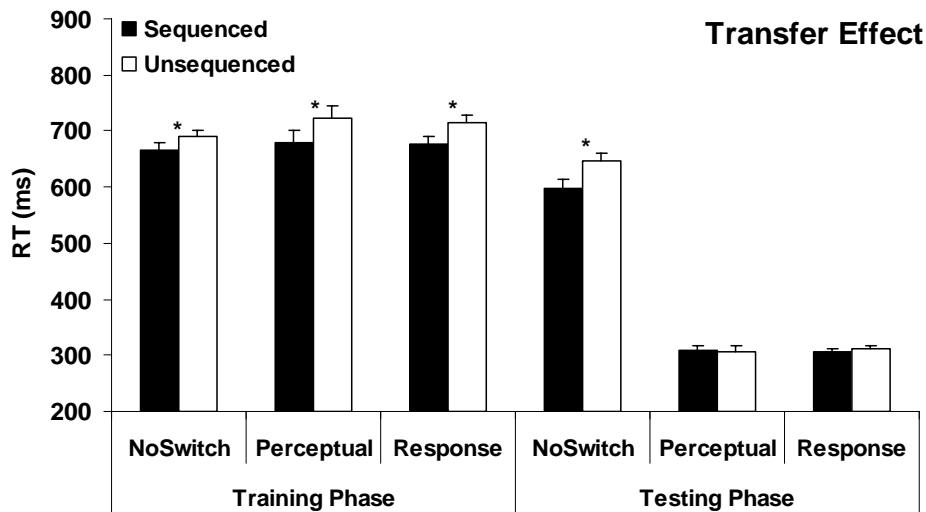


Figure 4. Training and Testing Phase Transfer Effects (Complete Data Set)

Mean RTs for the sequenced and unsequenced blocks used to calculate the transfer effect in both the training and testing phases in Experiment 1. Means are presented for each of the three experimental conditions (NoSwitch, Perceptual and Response). * $p < 0.05$.

2.3.1.1.5 Error Rates

Mean error rates were 2.9%, 2.8% and 3.7% for the NoSwitch, Perceptual and Response groups respectively. An arcsine transformation ($p' = \arcsin\sqrt{p}$; Kleinbaum, Kupper, Muller, & Nizam, 1998) was performed to stabilize the variance of the error rates. These data were submitted to a two-way ANOVA with a between-subjects variable for Group (NoSwitch, Perceptual, Response) and a within-subjects variable for Block (2-7). The test for sphericity was not significant ($p = 0.56$) so sphericity was assumed. The main effect of Block was significant, $F(5, 395) = 4.08, p < 0.01$. Neither the main effect of Group, $F(2, 79) = 1.74, p = 0.18$, nor the Block x Group interaction, $F(10, 395) = 0.66, p = 0.76$, were significant. Transfer effect error rates were also analyzed. Training phase transfer effects were not significant for the NoSwitch, $t(31) = 1.44, p = 0.08$, or the Response group, $t(25) = 0.97, p = 0.17$. The transfer effect for the Perceptual group was significant, $t(23) = 1.67, p = 0.05$; however, overall participants were less accurate on the slow unsequenced Block 8 (4.0%) compared to the fast sequenced Block 7 (3.5%), therefore, this significant effect is likely the result of the breakdown of the learned sequence and not evidence for a speed-accuracy trade off. None of the testing phase transfer effects were significant (NoSwitch, $t(31) = 1.21, p = 0.12$; Perceptual, $t(23) = 0.55, p = 0.29$; and Response, $t(25) = -0.24, p = 0.41$).

2.3.1.2 Discussion

Results from this analysis demonstrated that although participants in all of the groups were able to learn the sequence during the training phase, transfer of the acquired knowledge was not always successful when the mapping was altered during the testing phase. When both the sequence of stimuli and the sequence of responses were maintained across the

duration of the experiment, participants demonstrated knowledge of the sequence both during the training phase and during the testing phase. However, when the sequence of stimuli was maintained across the duration of the experiment, but the responses required were altered during the testing phase, previously acquired knowledge of the sequence was no longer beneficial at test. Similarly, when the both the physical responses and the response locations were maintained across all twelve blocks, but the sequence of stimuli was changed at test, knowledge acquired during the training phase was not manifest in the testing phase indicating a lack of knowledge transfer. Thus it seems that when either the sequence of stimuli or the sequence of responses alone are maintained, altering the opposite feature abolishes any RT benefit of sequence knowledge.

Power analyses revealed poor power (0.14) for detecting transfer effect difference during the training phase and very good power (0.95) for detecting transfer effect differences during the testing phase. Because of this high level power during the testing phase, we can be confident that the lack of transfer effect for both the Perceptual and Response groups is a real finding and not simply a failure to notice differences.

2.3.1.2.1 Explicit Knowledge

Free-generation test. The free-generation test was scored as in Willingham (1999). A free-generation score (the sum of all correct responses) was calculated for each participant. Not all correct responses had to be recalled consecutively, however, the correct response did have to be a part of a segment of at least three consecutive positions. For example, if the sequence was 3-4-3-1-2-4-1-3-2-1-4-2 and a participant produced the sequence 3-1-2-3-1-4-2 on the free-generation test, that participants' score would be 6 because 3-1-2 and 1-4-2 are both part of the original sequence. Mean recall scores were 6.6, 6.0 and 6.1 for the

NoSwitch, Perceptual and Response groups respectively. A one-way ANOVA was conducted and the main effect of Group was not significant, $F(2, 81) = 0.27, p = 0.76$.

2.3.2 Implicit Learners

2.3.2.1 Results

Previously, Willingham (1999; Experiment 1) demonstrated that removing participants with particularly large free-generation scores (indicative of greater explicit knowledge of the sequence) can alter the pattern of results dramatically. To explore this issue in the present study, I used Willingham's criterion for identifying participants with high levels of explicit knowledge by identifying participants who successfully produced 10 or more positions of the sequence during the free-generation task.

2.3.2.1.1 Excluded Participants

There were nine, four and five participants who met this criterion in the NoSwitch, Perceptual and Response groups respectively. These participants who demonstrated nearly complete explicit knowledge of the sequence were removed from the data set and the data were reanalyzed.

2.3.2.1.2 Reaction Times: Training Phase Sequenced Blocks

The same two-way ANOVA was run as in the original analysis and these data are plotted in Figure 5. These results closely mirrored the results of the original analysis. The test for sphericity was again significant ($p < 0.001$) so the Huynh-Feldt adjustment was used. Both the main effect of Block, $F(3.8, 234.4) = 55.70, p < 0.001$ and the Block x Group interaction, $F(7.6, 234.4) = 3.15, p < 0.01$, were significant. The main effect of Group, $F(2, 62) = 0.20, p = 0.82$, was not significant.

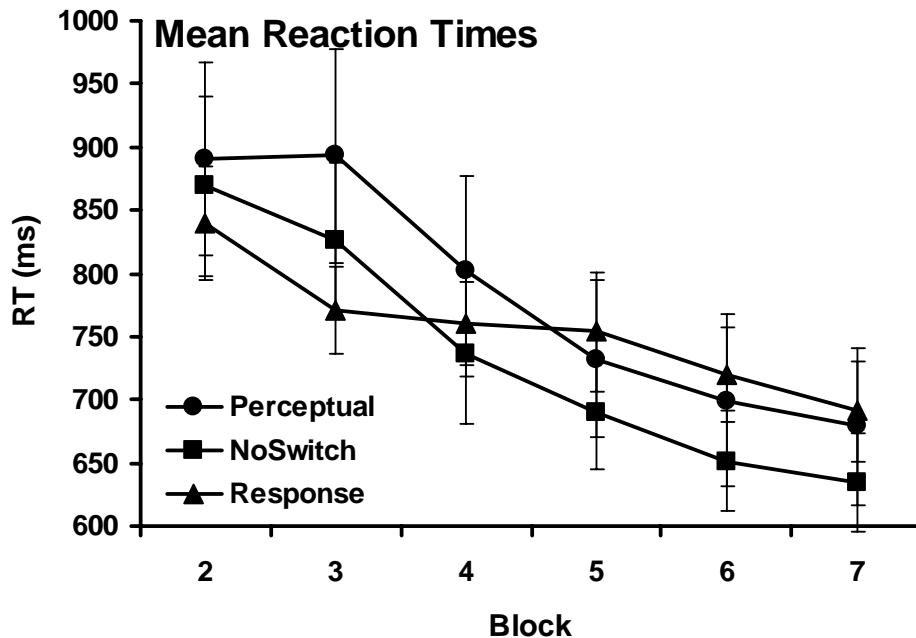


Figure 5. Training Phase Mean Reaction Times (Implicit Learners)
Mean RTs plotted across sequenced Blocks 2-7 for all three groups.

2.3.2.1.3 Training Phase Transfer Effect

The training phase transfer effect was again calculated for each group (Figure 6). When only participants who failed to demonstrate nearly complete explicit knowledge were considered, only the Response group showed a significant training phase transfer effect, $t(21) = 2.14, p < 0.05$. The training phase transfer effects for the NoSwitch, $t(22) = 1.21, p = 0.12$, and Perceptual, $t(19) = 1.32, p = 0.10$, groups were not significant. These data indicate that some of the participants who lacked explicit knowledge of the sequence also failed to achieve statistically significant transfer effects. It is important to note, however, that these participants likely did possess some knowledge of the sequence because group RT trends were in the direction of successful sequence learning. Additionally, when a Structure x Group repeated measures ANOVA was conducted, results revealed a significant main effect of Structure, $F(1, 62) = 7.16, p < 0.05$, but neither a main effect of Group, $F(2, 62) = 0.53, p$

= 0.59, nor a Structure x Group interaction, $F(2, 62) = 0.20, p = 0.82$. These data suggest that the training phase transfer effect was not significantly different between the three groups.

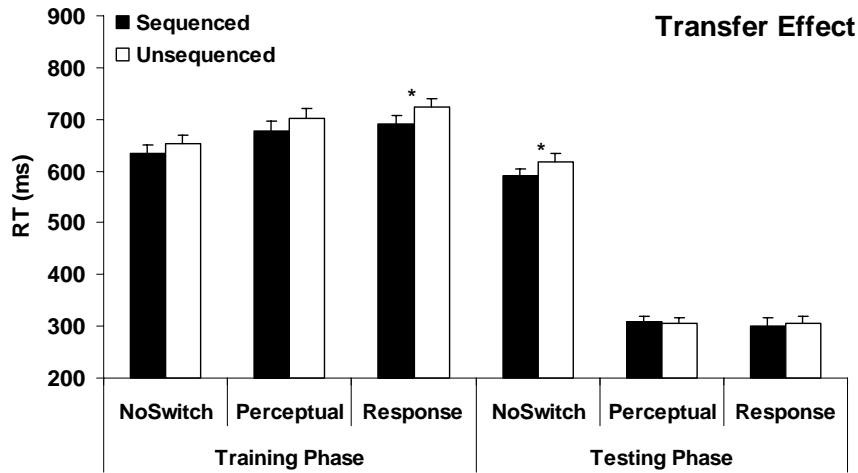


Figure 6. Training and Testing Phase Transfer Effects (Implicit Learners)
Mean RTs for the transfer effect in both the training and testing phases for all three groups (NoSwitch, Perceptual, Response). * $p < 0.05$.

2.3.2.1.4 Testing Phase Transfer Effect

Testing phase transfer effects were calculated for the three groups; these data also presented in Figure 6. This effect was significant for the NoSwitch group, $t(22) = 3.27, p < 0.001$, but not for the Perceptual, $t(19) = -0.23, p = 0.41$, or the Response, $t(21) = 0.78, p = 0.22$, groups. A Structure x Group repeated measures ANOVA revealed a significant main effect of Group, $F(2, 62) = 49.98, p < 0.001$. There was a trend toward significance for both the main effect of Structure, $F(2, 62) = 2.81, p = 0.10$, and the Structure x Group interaction, $F(1, 62) = 2.42, p = 0.10$.

2.3.2.1.5 Error Rates

Mean error rates were 2.9%, 2.6% and 4.0% for the NoSwitch, Perceptual and Response groups respectively. Arcsine transformed data were submitted to the same two-

way ANOVA as in the previous error analysis. The test for sphericity was not significant ($p = 0.84$) so sphericity was assumed. The main effect of Block was again significant, $F(5, 310) = 3.66, p < 0.01$. Neither the main effect of Group, $F(2, 62) = 2.24, p = 0.12$, nor the Block x Group interaction, $F(10, 310) = 0.50, p = 0.89$, were significant. *T*-tests were performed on these error data to assess transfer effect accuracy differences. None of the transfer effects were significant both during the training phase (NoSwitch, $t(22) = 1.04, p = 0.16$; Perceptual, $t(19) = 1.09, p = 0.14$; and Response, $t(21) = 1.23, p = 0.12$) and during the testing phase (NoSwitch, $t(22) = 1.30, p = .10$; Perceptual, $t(19) = 0.79, p = 0.22$; and Response, $t(21) = -0.04, p = 0.48$).

2.3.2.2 Discussion

When participants with extensive explicit knowledge of the sequence were removed from the analysis, overall participants still demonstrated a reduction in mean RTs across blocks 2-7. The nature of this analysis does not allow us to differentiate between RT improvement resulting from increased sequence learning and general improvements in performing the task. It is for this reason that we look specifically at the transfer effects. When only the implicit learners were considered, the training phase transfer effect data changed considerably compared to when the entire data set was analyzed. These data indicate that at least some of the participants who demonstrated low levels of explicit awareness on the free-generation task, also failed to demonstrate a training phase transfer effect indicating that they were not as successful in learning the sequence. This suggests that participants who achieved substantial explicit knowledge of the sequence largely drove the significant training phase transfer effect in the original analysis. Figure 7 plots the difference scores (unsequenced Block 8 minus sequenced Block 7; this is a single digit that quantifies

the transfer effect difference for each participant) for each group. It is evident here that explicit learners indeed showed larger training phase transfer effects than implicit learners.

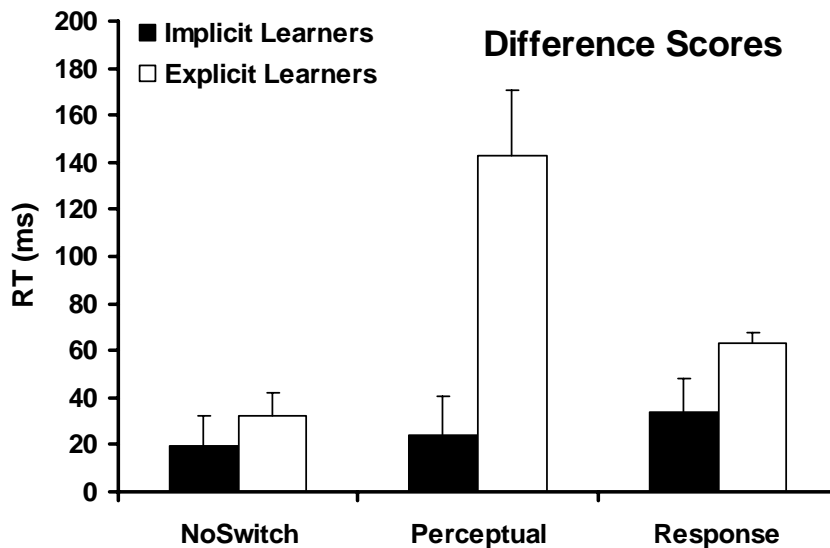


Figure 7. Implicit vs. Explicit Learner Training Phase Difference Scores. During the training phase, explicit learners showed larger transfer effects than implicit learners.

These data are interesting because although the method closely resembles Willingham's (Willingham, 1999) Experiment 3, the results are quite different. When he considered only those participants without high levels of explicit sequence knowledge, Willingham found significant testing phase transfer effects for the Motor group (Response group equivalent), and a trend toward significance for his Perceptual group. When the same subset of participants was analyzed in the current experiment neither the Response group nor the Perceptual group showed evidence for testing phase sequence knowledge. A power analysis was performed on the transfer data revealing very poor power (0.08) during the training phase and poor power (0.54) during the testing phase. It is possible that the results

of the analysis of implicit learners in this study are very different from Willingham's results because there was not enough power in the present study to detect the transfer effect differences that Willingham reported. The following analysis suggests that this is unlikely.

2.3.3 Training Phase Learners

2.3.3.1 Results

2.3.3.1.1 Excluded Participants

When explicit learners were excluded from the analysis, some of the remaining participants were unsuccessful in learning the sequence during the training phase. In fact, eight, five, and eight participants in the NoSwitch, Perceptual and Response groups respectively showed no evidence (Block 8 faster than Block 7) of sequence learning during the training phase. Because this study sought to identify what precisely is learned when participants implicitly learn a sequence, including participants who did not learn during the training phase contaminated the data set. The most direct test, therefore, for identifying the locus of implicit sequence learning would be to include only participants who demonstrate evidence of successful sequence learning during the training phase. Thus, the data were reanalyzed again including only those implicit learners with a positive transfer effect (Block 7 faster than Block 8) during the training phase.

2.3.3.1.2 Reaction Times: Training Phase Sequenced Blocks

Mean data were again analyzed using a two-way ANOVA with a between-subjects variable for Group (NoSwitch, Perceptual, Response) and a within-subjects variable for block (2-7). As in the previous two such analyses, the sphericity assumption did not hold ($p < 0.01$) and the Huyhn-Feldt adjustment was used. There was a significant main effect of Block, $F(4.2, 174.0) = 42.91, p < 0.001$, and the main effect of Group was not significant,

$F(2, 41) = 2.08, p = 0.14$. The Block x Group interaction showed a trend toward significance, $F(8.5, 174.0) = 1.80, p = 0.08$. These data are presented in Figure 8.

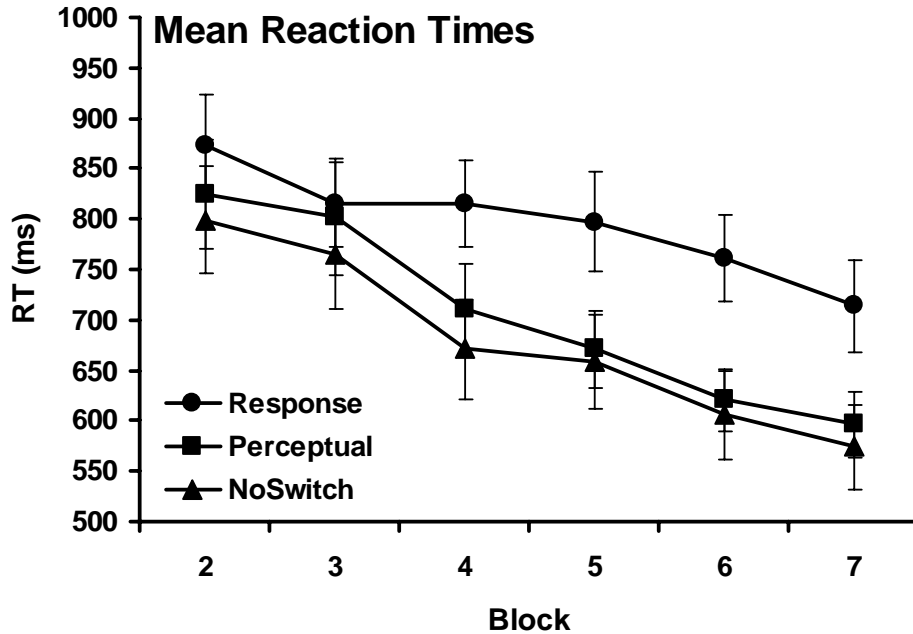


Figure 8. Training Phase Mean Reaction Times (Training Phase Learners)
Mean RTs across sequenced Blocks 2-7 for all three groups.

2.3.3.1.3 Training Phase Transfer Effect

T-tests were performed comparing mean RTs on unsequenced Block 8 and sequenced Block 7. The mean RTs are presented in Figure 9. This training phase transfer effect was statistically significant for all of the groups; NoSwitch, $t(14) = 4.9, p < 0.001$; Perceptual, $t(14) = 6.66, p < 0.001$; and Response, $t(13) = 4.37, p < 0.001$. A Structure by Group ANOVA was performed on these data. The main effect of Structure, $F(1, 41) = 75.60, p < 0.001$, was significant. The main effect of Group, $F(2, 41) = 3.49, p < 0.05$, was also significant with the Response group performing significantly slower ($p < 0.05$) than the

NoSwitch group. There were no other significant group differences. The Structure x Group interaction, $F(2, 41) = 0.23, p = 0.79$, was not statistically significant.

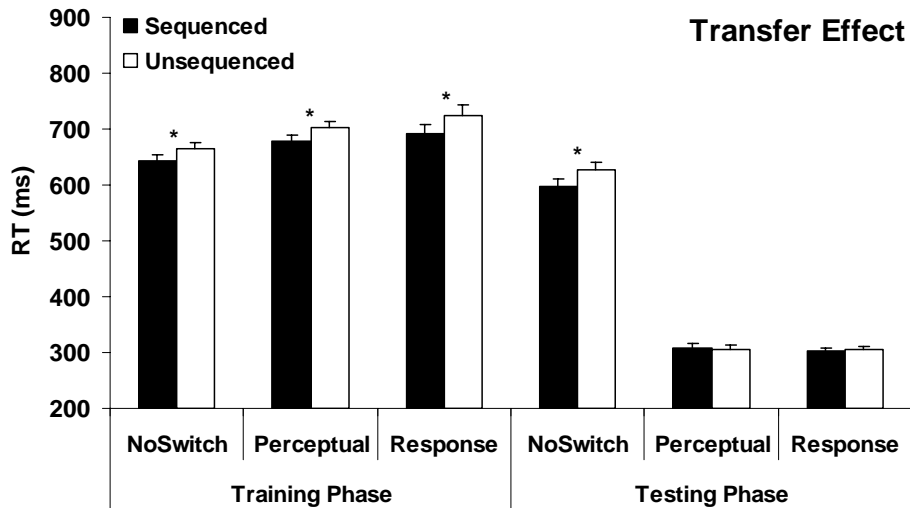


Figure 9. Training and Testing Phase Transfer Effects (Training Phase Learners)
 Mean RTs for the transfer effect in both the training and testing phases in Experiment 1. Means are presented for each of the three experimental conditions (NoSwitch, Perceptual and Response). * $p < 0.05$.

2.3.3.1.4 Testing Phase Transfer Effect

Testing phase transfer effects were calculated for these participants. These data are also plotted in Figure 9. The transfer effect was statistically significant only for the NoSwitch group, $t(14) = 2.72, p < 0.01$, and was not significant for the Perceptual, $t(14) = -0.99, p = 0.17$, or the Response, $t(13) = 1.20, p = 0.13$, groups. A Structure x Group repeated measures ANOVA was conducted. The main effect of Structure, $F(1, 41) = 4.40, p < 0.05$, the main effect of Group, $F(2, 41) = 43.58, p < 0.001$, and the Structure x Group interaction, $F(1, 41) = 5.74, p < 0.01$, were all statistically significant.

2.3.3.1.5 Error Rates

Mean error rates were 2.5%, 2.8% and 4.1% for the NoSwitch, Perceptual and Response groups respectively. Arcsine transformed data were again submitted to the same two-way ANOVA as in the previous error analysis. The test for sphericity was not significant ($p = 0.78$) so sphericity was assumed. The main effect of Block was again significant, $F(5, 205) = 2.75, p < 0.05$. The Block x Group interaction, $F(10, 205) = 0.85, p = 0.58$, was not significant and the main effect of Group, $F(2, 41) = 2.97, p = 0.06$, showed a trend toward significance. When submitted to paired-sample t -test to evaluate mean error rates when participants were transferred from sequenced to unsequenced trials, none of the groups showed significant transfer effects during either the training (NoSwitch, $t(14) = 1.30, p = 0.11$; Perceptual, $t(14) = 1.00, p = 0.17$; and Random, $t(13) = 0.93, p = 0.18$) or testing (NoSwitch, $t(14) = 0.87, p = 0.20$; Perceptual, $t(14) = 1.05, p = 0.18$; and Response, $t(13) = 1.67, p = 0.06$) phases.

2.3.3.2 Discussion

This analysis provided the purest assessment of implicit sequence knowledge transfer from training to test. It included only participants who implicitly learned the sequence during the training phase. Analyzing the performance of only this subset of participants provided optimal conditions for a transfer of the acquired sequence knowledge to the testing phase. Under such optimal conditions, neither the Perceptual group in which the sequence of stimuli was maintained from the training phase nor the Response group in which the sequence of button pushes was maintained from the training phase showed a significant transfer effect at test. Like the data from the original analysis, these data do not support either the stimulus-based or the response-based theories of sequence learning. Again, power analyses revealed poor power (0.09) for detecting transfer effect differences during the

training phase, but very good power (0.90) for detecting transfer effect differences during the testing phase. It is therefore unlikely that the lack of a significant transfer effect in both the Perceptual and Response groups is the result of a failure to detect a difference between sequenced and subsequence blocks.

2.4 Experiment 1 Conclusions

The results from Experiment 1 are inconsistent with both the perceptual and response-based accounts of sequence learning. If the perceptual sequence is learned during the training phase of the experiment, participants in the Perceptual group should show a significant transfer effect during the testing because the visual sequence has not changed. That is knowledge from the training phase should transfer to the testing phase because the critical feature has not changed. The present results do not support this theory. Similarly, if it is the response sequence (Willingham, 1999) that is learned, than Response group participants should show learning during the testing phase when the sequence of button pushes is maintained. Additionally, if the series of response locations is learned during the training phase (Willingham, 2000), then the Response group should show a transfer effect during the testing phase because the response location, in addition to the actual motor action, remains the same from training to test. Data from the Response group are inconsistent with these hypotheses.

The present results are, however, consistent with the data from my year project (Schwarb & Schumacher, 2006) that suggested that response selection is important for sequence learning and that sequence learning uses S-R rule systems (Duncan, 1977). These current results demonstrate that it is only when the S-R rules remain the same from training to test that sequence learning transfers from one phase to the next. These data area also

consistent with Willingham, Nissen and Bullemer's (1989) idea that sequence learning is neither stimulus nor motor-based but rather based on learning a system of S-R rules.

In essence, Experiment 1 was designed to replicate Willingham's (1999) Experiment 3 with a few necessary modifications in an attempt to cleanup some of the potential confounds in the original experiment. It is possible that these confounds obscured Willingham's data and that is why his findings are inconsistent with those reported here. The current study made three key modifications.

The first was the addition of three sequenced blocks to the training phase. The effect of this modification were two fold. First, it equalized training phase performance so that there were no longer large RT differences between the groups when the transfer block was introduced. In the Willingham study, on the block preceding the transfer block, the Motor group (the equivalent of the Response group in the current study) was still approximately 60 ms slower than the Perceptual group. In the current experiment, all groups were responding within 13 ms of each other on the block before the transfer block. Second, adding more sequenced blocks increased the likelihood that learning would occur. In the Willingham experiment, when the transfer effect data was considered, there were no significant group differences; however, not all of the groups had difference scores (unsequenced Block 4 minus sequenced Block 3) that were significantly greater than zero (null result). In this study, there were no significant differences between the groups and all groups had difference scores (unsequenced Block 8 minus sequenced Block 7) that were statistically greater than zero. The current study sought to identify what features of the sequence needed to remain constant for learning to be expressed during the testing phase. This first modification optimized the design by facilitating similar training phase performance among the groups.

This was important so that any testing phase differences could not be attributed to training phase differences.

The second modification was the addition of one extra unsequenced block at the beginning of the testing phase. This modification allowed us to use the traditional method for calculating the transfer effect (e.g., RTs from the sequenced block compared to averaged RTs from the surrounding unsequenced blocks). Willingham did not calculate his transfer effect as such because he was concerned that the block preceding the sequenced block was contaminated as participants adjusted to the new mapping.

The third modification was that the present experiment implemented a different indirect response mapping than that used by Willingham (1999). The training phase indirect mapping in the current study was not at all related to the testing phase direct mapping, whereas the indirect and direct mappings in the Willingham study were highly related. In the Willingham study, the direct mapping required participants to respond with the button directly below the target and the indirect mapping required participants to respond with the button one position to the right of the target. In S-R rule terms, it is possible that participants were able to use a transformation of the S-R rules (“shift response one position over”) required by the mapping used in the training phase during the testing phase. This was not the case with the mappings used in the present study which necessitated entirely different sets of S-R rules during the training and testing phases. This modification allows us to conclude that Willingham’s Motor group expressed sequence knowledge during the training phase because they were able to continue to use the same set of rules during both phases of the experiment. In Experiment 1, however, the Response group was unable to transfer their knowledge from training to test because each phase required a different set of S-R rules.

CHAPTER 3: EXPERIMENT 2

3.1 Introduction

The results from Experiment 1 provide support for the importance S-R rules when learning a sequence. As stated previously, unlike S-R associations, S-R rules are not restricted to the physical attributes of the stimuli and they are likely inclusive of the more general mental representation of the stimulus (Kornblum, Hasbroucq, & Osman, 1990; Wickens, Sandry, & Vidulich, 1983). For this reason, S-R mappings may exist across modalities and the same response can be made to matched stimuli in different modalities (Kornblum, Hasbroucq, & Osman, 1990).

For example, Willingham (1999, Experiment 2) conducted a variation of the standard SRT task in which he trained participants on a sequence in which the stimuli were either spatial locations (four possible target locations) or digits (1-4). Participants responded with their left middle finger for both the digit “1” and the leftmost circle, their left index finger for both the digit “2” and the central left circle, their right index finger for both the digit “3” and the central right circle and their right middle finger both for the digit “4” and the rightmost circle. After participants had been trained for 3 blocks in either the spatial or the digits condition, the testing phase began and everyone responded to spatial stimuli. A transfer block was introduced and both the spatial and the digits groups showed significant sequence learning at test. Willingham concluded that sequence learning must not be purely perceptual because although the stimuli were altered, sequence learning persisted; similarly, he concluded that sequence learning is not supported by S-R pairings because the stimuli were altered, thus disrupting the S-R bond.

However, these data are consistent with the S-R rules hypothesis that suggests that it is not the physical characteristics of the stimuli that is critical; rather it is the mental representation that matters (Kornblum, Hasbroucq, & Osman, 1990; Wickens, Sandry, & Vidulich, 1983). In Experiment 2 of the Willingham (1999) study, there was a direct correspondence between, for example, the response made to the digit “1” and the first spatial location. Conceptually these stimuli are highly similar as they are both the first possible location or the first possible digit. Their mental representation is the same and therefore the S-R rules learned when responding to the digit stimuli can also be applied to the spatial stimuli. In Kornblum and colleagues’ terms, the spatial and digit stimuli share considerable dimensional overlap and response selection develops quickly because the correct response code is already primed. Thus the very same S-R rules can be applied to both sets of stimuli and as a result, sequence learning is unimpaired when the switch from digit to spatial stimuli is made.

Experiment 2 sought to demonstrate that sequence learning is supported by the learning of S-R rules that are neither restricted by the physical nature of the stimulus nor the modality of the response; an idea consistent with the predictions of the S-R rules hypothesis and inconsistent with both the sequence learning is perceptual and sequence learning is based on response location accounts (Table 2). The S-R rule theory predicts that sequence learning will persist so long as the S-R rules remain unchanged. Changing only the stimulus or response modality should not be sufficient to disrupt the RT benefit of having learned the sequence. The response-based theory of sequence learning predicts that simply changing the response modality would be sufficient to disrupt sequence learning because the location of response changes. The stimulus-based theory predicts that changing the stimuli (e.g., from

spatial locations to alphanumeric symbols) should be sufficient to disrupt learning because the stimuli are altered.

Table 2. Predicted Results for Each Theory of Sequence Learning

		Theory		
		Perceptual	Response Location	S-R Rule
Group	Control	Yes	Yes	Yes
	Spatial/Indirect	Yes	No	Yes
	Spatial/Direct	Yes	No	No
	Digits/Indirect	No	No	Yes

Predications for whether or not learning will be demonstrated in the testing phase for each of the three theories (Learning is perceptual, learning is based on response locations and learning is contingent on S-R rules) in Experiment 2

3.2 Method

3.2.1 Participants

Seventy-two participants from the Georgia Institute of Technology participated in this study in partial fulfillment of a course requirement. None of the participants were aware of the purpose of the study. Participants were given informed consent prior to beginning the experiment and all participants were treated in accordance with APA guidelines.

3.2.2 Stimuli and apparatus.

Stimuli and apparatus were identical to Experiment 1 except that digit stimuli were used in addition to spatial stimuli. The digits were 1, 2, 3 and 4. The “1” subtended 0.6° x 3.5° of visual angle and the “2,” “3” and “4” each subtended 2.5° x 3.5° of visual angle. The

digits appeared centrally for 100 ms and were then replaced by a fixation cross that subtend 1.0° x 1.0° of visual angle.

3.2.3 SRT task.

Participants were randomly assigned to one of four groups: NoSwitch, Spatial/Direct, Spatial/Indirect, and Digits/Indirect. All participants performed 14 blocks of 96 trials each. The SRT task was as in Experiment 1 during the training phase (Blocks 1-10) with the addition of two extra blocks. During the testing phase (Blocks 11-14), some groups continued making manual responses, while others switched to verbal responses. During the testing phase, the NoSwitch group continued to perform the spatial-SRT task using the indirect manual S-R mapping. During the testing phase, participants in the Spatial/Indirect and Spatial/Direct saw the same stimuli (spatial) as in the training phase but they responded verbally by saying “one,” “two,” “three,” or “four”. The Digits/Indirect group also made verbal responses, but they did not see spatial stimuli but rather the centrally presented digits 1, 2, 3 and 4. The digit “1” corresponded to the leftmost spatial location in the training phase, the digit “2” corresponded to the central left spatial location and so on. The Spatial/Direct group used a direct S-R verbal mapping in which participants responded to the spatial stimuli from left to right by responding “one,” “two,” “three” and “four” (Figure 10). The Spatial/Indirect group responded using an indirect S-R verbal mapping that directly corresponds to the indirect S-R manual mapping used during the training phase. Responses that were made with the left middle finger during training were made instead by saying “one,” responses made with the left index finger will be made instead by saying “two,” responses made with the right index finger will be made instead by saying “three” and responses made with the right middle finger will be made instead by saying “four” (Figure

10). The Digits/Indirect group used the same indirect S-R verbal mapping as the Spatial/Indirect group, but the stimuli were digits.

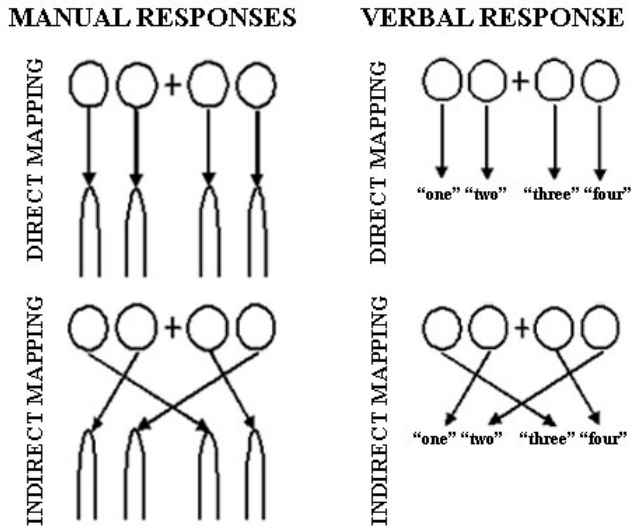


Figure 10. Direct and Indirect S-R Mappings for Both Response Modalities

Direct and Indirect S-R mappings for both manual and verbal responses in Experiment 2. The circles are the possible target locations and the arrows indicate which manual or verbal response should be used when a target appears in a given location.

3.2.4 The sequence.

The sequences used were as in Experiment 1.

3.2.5 Procedure.

The procedure was identical to that of Experiment 1 with three exceptions. First, during the testing phase, all participants Spatial/Indirect, Spatial/Direct and Digits/Indirect groups made verbal responses. Second, the Digits/Indirect group responded to digit stimuli rather than spatial stimuli. Finally, only the Spatial/Direct group used the direct S-R mapping at test, the other groups used the indirect S-R mapping during the testing phase.

3.3 Results and Discussion

3.3.1 Complete Data Set

3.3.1.1 Results

3.3.1.1.1 Excluded Participants

One participant from the NoSwitch group was removed from the analysis because his training phase learning score was more than three standard deviations below the mean.

3.3.1.1.2 Reaction Times

As in Experiment 1, mean data were analyzed with a two-way ANOVA with a between-subjects variable for Group (NoSwitch, Spatial/Direct, Spatial/Indirect, Digits/Indirect) and a within-subjects variable for block (2-9). Mauchley's test of was significant ($p < 0.001$), so the degrees of freedom were corrected according to the Huynh-Feldt adjustment. The ANOVA revealed a significant main effect of Block, $F(4.8, 326.8) = 46.77, p < 0.001$, indicating that each group got significantly faster across the eight practice blocks. Neither the main effect of Group, $F(3, 68) = 0.86, p = 0.47$, nor the Block x Group interaction, $F(14.4, 326.8) = 1.36, p = 0.13$, were statistically significant. These data are plotted in Figure 11.

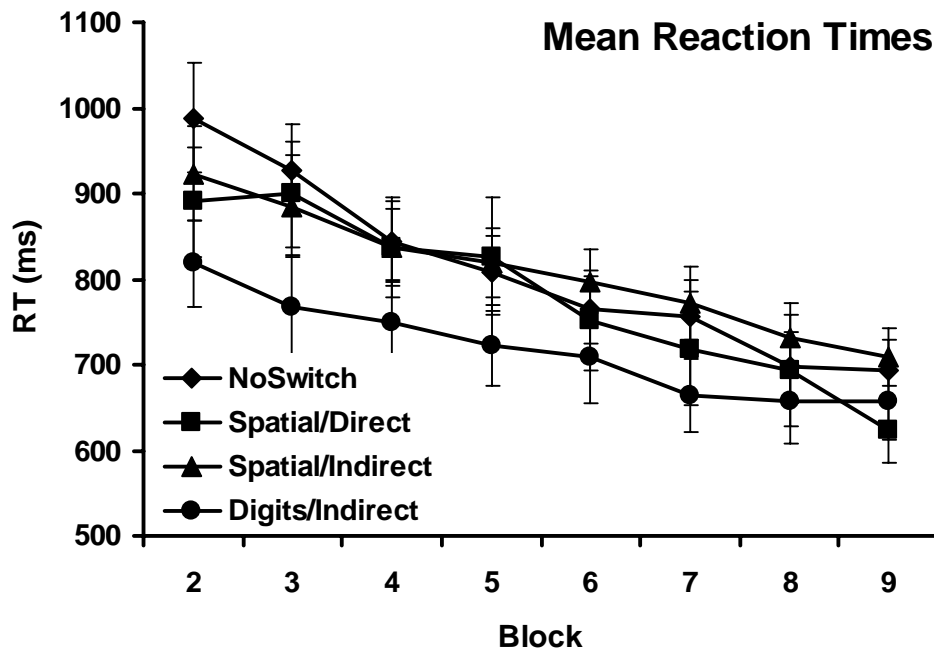


Figure 11. Training Phase Mean Reaction Times (Complete Data Set)
Mean RTs across sequenced Blocks 2-9 for all four groups.

3.3.1.1.3 Training Phase Transfer Effect

As in Experiment 1, the transfer effect was of particular interest to the current study. Training phase transfer effects were calculated by comparing mean RTs on Block 10 to mean RTs on Block 9. Again, due to the specificity of this transfer effect prediction, one-tailed comparisons were used in all tests of the transfer effect. As shown in Figure 12, mean RTs on Block 10 were slower than mean RTs on Block 9, however, these differences were not significant for all of the groups. The transfer effect was significant for the Spatial/Direct group, $t(18) = 2.92, p < 0.001$, and approached significance for the NoSwitch group, $t(17) = 1.62, p = 0.06$. The training phase transfer effect was not significant for either the Spatial/Indirect group, $t(16) = 0.91, p = 0.19$, or the Digits/Indirect group, $t(17) = 1.11, p = 0.14$, however, raw RTs are in the direction of learning. These group differences are

surprising considering that the task was identical for all four groups during the training phase.

A two-way repeated measures ANOVA with Structure (Sequenced, Unsequenced) as a within subjects variable and Group (NoSwitch, Spatial/Direct, Spatial/Indirect, Digits/Indirect) as a between subject variable was conducted on the training phase transfer data. There was a significant main effect of Structure, $F(1, 68) = 10.43, p < 0.01$, indicating that RTs from Block 9 were significantly faster than RTs on Block 10 (evidence for sequence learning). Neither the main effect of Group, $F(3, 68) = 0.71, p = 0.55$, nor the Structure x Group interaction, $F(3, 68) = 0.67, p = 0.57$, were significant. These results indicate that the transfer effects were not significantly different among the four groups.

3.3.1.1.4 Testing Phase Transfer Effect

Transfer effects were calculated in the testing phase by conducting a *t*-test between the mean RTs from the averaged surrounding unsequenced Blocks 12 and 14 and the mean RT on sequenced Block 13. These data are also plotted in Figure 12. None of the groups demonstrated a significant testing phase transfer effect. The NoSwitch group demonstrated a trend toward significance, $t(17) = 1.65, p = 0.06$. Despite being non-significant, transfer effects for the NoSwitch and Digits/Indirect, $t(17) = 1.15, p = 0.13$, groups were in the expected direction of expressed testing phase sequence knowledge. Significance tests were not conducted on the testing phase transfer effects for either the Spatial/Direct or the Spatial/Indirect group because RT trends were opposite of the predicted direction. A two-way Structure by Group ANOVA revealed a significant main effect of Group, $F(3, 68) = 29.60, p < 0.001$, driven by the fact that the groups using the indirect verbal mapping were slower to respond than the groups who used the direct verbal mapping and the indirect

manual mapping. Neither the main effect of Structure, $F(1, 68) = 0.54, p = 0.47$, nor the Structure x Group interaction, $F(3, 68) = 1.54, p = 0.21$, was significant.

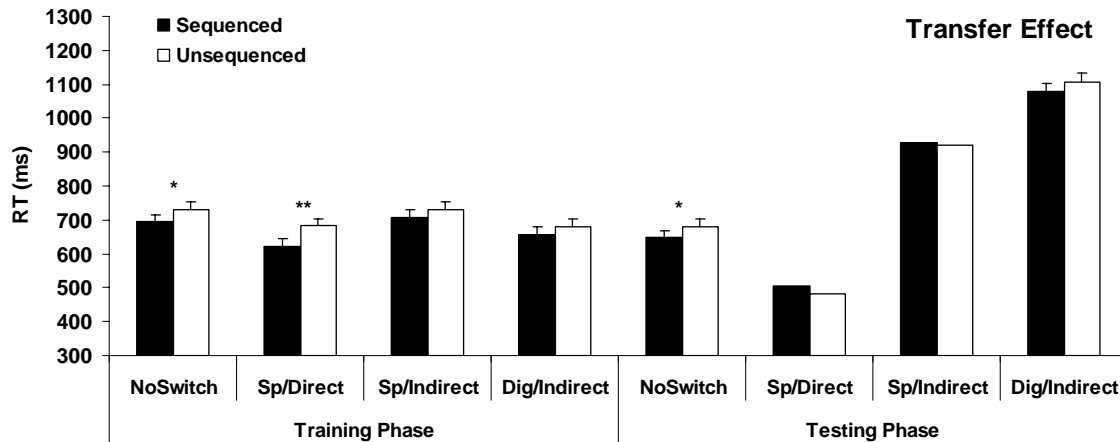


Figure 12. Training and Testing Phase Transfer Effects (Complete Data Set)

Mean RTs for the sequenced and unsequenced blocks used to calculate the transfer effect in both the training and testing phases in Experiment 2. Means are presented for each of the four experimental conditions (NoSwitch, Spatial/Direct, Spatial/Indirect, Digits/Hard). ** $p < 0.05$, * $p < 0.10$.

3.3.1.1.5 Error Rates

Mean error rates were 3.2%, 2.5%, 3.6% and 4.2% for the NoSwitch, Spatial/Direct, Spatial/Indirect and Digits/Indirect groups respectively. As in Experiment 1, an arcsine transformation ($p' = \arcsin\sqrt{p}$; Kleinbaum, Kupper, Muller, & Nizam, 1998) was performed to stabilize the variance of the error rates. These data were then submitted to a two-way ANOVA with a between-subjects variable for Group (NoSwitch, Spatial/Direct, Spatial/Indirect, Digits/Indirect) and a within-subjects variable for Block (2-9). The test for sphericity was not significant ($p = 0.11$) indicating that the sphericity assumption was not violated. The main effect of Block, $F(7, 476) = 2.17, p < 0.05$, was significant, indicating that participants got significantly more accurate across Blocks 2-9. Neither the main effect

of Group, $F(3, 68) = 0.59, p = 0.62$, nor the Block x Group interaction, $F(21, 476) = 0.83, p = 0.69$, were significant. Transfer effect error rates were also analyzed. None of the training phase transfer effects were significant: NoSwitch, $t(17) = -0.384, p = 0.71$, Spatial/Direct, $t(18) = -0.25, p = 0.80$, Spatial/Indirect, $t(16) = 0.50, p = 0.62$, and Digits/Indirect, $t(17) = -1.00, p = 0.33$. Additionally, none of the testing phase transfer effects were significant: NoSwitch, $t(17) = 0.53, p = 0.30$, Spatial/Direct, $t(18) = -0.89, p = 0.19$, Spatial/Indirect, $t(16) = -1.05, p = 0.16$, and Digits/Indirect, $t(17) = 0.10, p = 0.46$.

3.3.1.2 Discussion

When all participants were considered, the data are rather surprising. First, although the training phase task was identical for all participants in all groups, t -tests showed that transfer effects were not significant for all of the groups. However, an ANOVA revealed that these group differences were not significant and that all participants learned the sequence during the training phase.

During the testing phase, only the NoSwitch group showed near significant transfer of sequence knowledge from training to test. The Digits/Indirect group showed RT trends in the direction consistent with expression of sequence knowledge, however, this trend did not reach significance. Both the Spatial/Direct and Spatial/Indirect group did not show any evidence of sequence knowledge at test, and in fact, RTs for the sequenced block were slower than the averaged RTs for the surrounding unsequenced blocks so no statistical tests were conducted. This pattern is the opposite of that predicted by sequence learning. Despite these seeming differences, an ANOVA revealed that the Structure x Group interaction was not statistically significant. This means that the testing phase transfer effects were not

different among the four groups; that is, there was no evidence for testing phase sequence knowledge for any of the groups.

It is important to note here that a power analysis revealed that power for detecting transfer effect differences was quite poor both during the training (0.18) and testing (0.40) phases. This means that though transfer effect differences may have existed, there was not enough power available to identify them, or rather there is a possibility that a type-II error has been committed.

3.3.1.2.1 Explicit Knowledge

Free-generation test. The free-generation test was scored as in Experiment 1. Mean recall scores were 6.5, 5.3, 7.1 and 6.1 for the NoSwitch, Spatial/Direct, Spatial/Indirect and Digits/Indirect groups respectively. A one-way ANOVA was conducted and the main effect of Group was not significant, $F(3, 71) = 0.93, p = 0.43$.

3.3.2 Implicit Learners

3.3.2.1 Results

Again, as in Willingham (1999) and Experiment 1 of the current study, we removed all participants who demonstrated exceptionally high levels of explicit sequence knowledge on the free-recall test (scores of 10 or higher) for this second analysis.

3.3.2.1.1 Excluded Participants

There were six, two, three and three participants who demonstrated high levels of explicit knowledge in the NoSwitch, Spatial/Direct, Spatial/Indirect and Digits/Indirect groups respectively. These participants were removed from the analysis.

3.3.2.1.2 Reaction Times

The same two-way ANOVA was run as in the previous analyses. The test for sphericity was significant ($p < 0.001$) so the Huynh-Feldt correction was used to adjust degrees of freedom. The main effect of Block, $F(5.0, 266.7) = 41.70, p < 0.001$, was significant indicating that participants got faster across blocks. Neither the main effect of Group, $F(3, 53) = 0.96, p = 0.42$, nor the Block x Group interaction, $F(15.1, 266.7) = 1.01, p = 0.44$, were significant. These data are plotted in Figure 13.

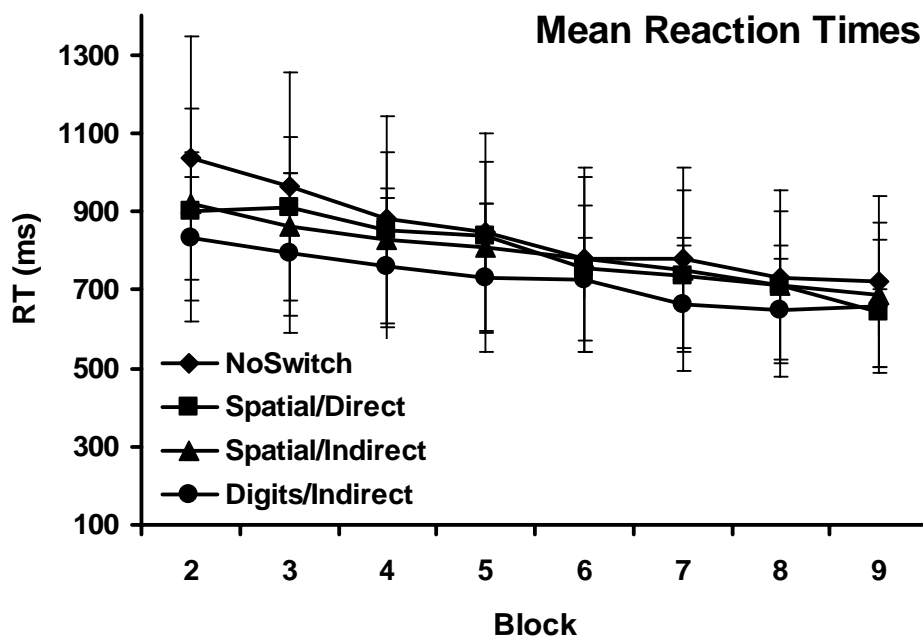


Figure 13. Training Phase Mean Reaction Times (Implicit Learners)
Mean RTs plotted across sequenced Blocks 2-9 for all four groups.

3.3.2.1.3 Training Phase Transfer Effect

As in Experiment 1, after explicit learners were removed from the analysis, not all of the groups demonstrated significant training phase transfer effects, however, this is not surprising as it was also the case when the entire data set was considered. Transfer effects were significant for the Spatial/Direct, $t(16) = 2.68, p < 0.05$, and Spatial/Indirect, $t(13) =$

1.81, $p < 0.05$, groups. The NoSwitch, $t(11) = 1.31$, $p = 0.11$, and Digits/Indirect, $t(14) = 0.44$, $p = 0.34$ group did not demonstrate significant transfer effects, although the raw RT data is in the direction indicative of sequence learning. Thus it seems that not all of the implicit learners were able to learn enough about the sequence to show a significant transfer effect during the training phase (Figure 14).

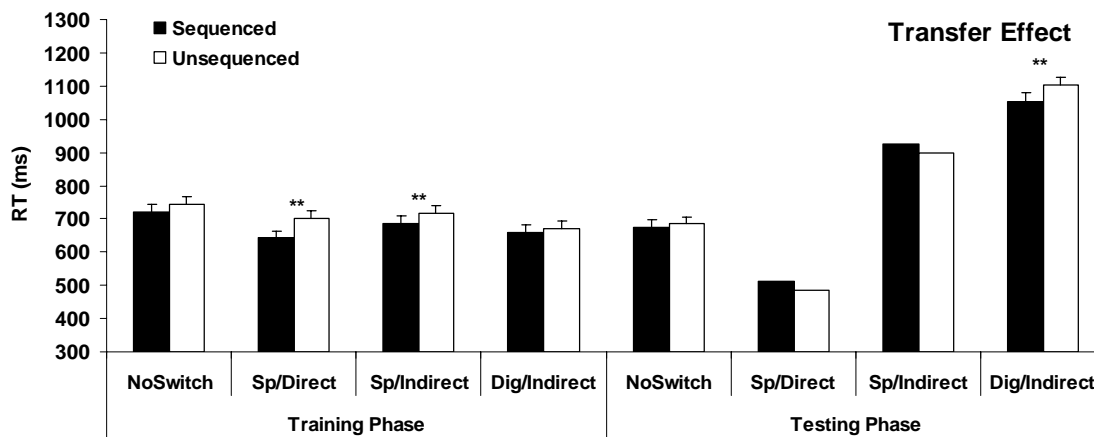


Figure 14. Training and Testing Phase Transfer Effects (Implicit Learners)

Mean RTs for the transfer effect in both the training and testing phases for all four groups. ** $p < 0.05$, * $p < 0.10$.

As in the previous analysis, a Structure by Group ANOVA revealed a significant main effect of Structure, $F(1, 53) = 9.07$, $p < 0.01$. The main effect of Group $F(3, 53) = 0.73$, $p = 0.54$, and the Structure x Group interaction $F(3, 53) = 0.88$, $p = 0.46$, were not significant. This indicates that sequence learning did occur and was not significantly different among the groups.

3.3.2.1.4 Testing Phase Transfer Effect

Transfer effects were calculated for all four groups (Figure 14). The Digits/Indirect transfer effect achieved statistical significance, $t(14) = 1.98$, $p < 0.05$. The transfer effect for

the NoSwitch group was not significant, $t(10) = 0.22, p = 0.11$, however, the trend in RTs indicated that there was likely some transfer of sequence knowledge. As was the case when the entire data set was analyzed, at test both the Spatial/Direct and Spatial/Indirect groups showed RT trends in the direction opposite to that predicted by sequence learning and were therefore statistical tests were not performed.

A two-way Structure by Group ANOVA was also conducted on the testing phase transfer data. The main effect of Structure $F(1, 53) = 0.01, p = 0.92$, was not significant. The main effect of Group $F(3, 53) = 21.24, p < 0.001$, was significant and again driven by slow indirect verbal mapping responses and faster direct verbal and indirect manual mapping responses. The Structure x Group interaction $F(3, 53) = 2.99, p < 0.05$, was also statistically significant indicating that there were transfer effect differences among the four groups.

3.3.2.1.5 Error Rates

Mean error rates were 2.8%, 2.5%, 3.8% and 3.9% for the NoSwitch, Spatial/Direct, Spatial/Indirect and Digits Hard groups respectively. Arcsine transformed data were then submitted to the same two-way ANOVA as in the previous error analyses. The test for sphericity was not significant ($p = 0.34$) and thus sphericity was assumed. Neither the main effect of Block, $F(7, 371) = 1.59, p = 0.14$, the main effect of Group $F(3, 53) = 0.68, p = 0.57$, nor the Block x Group interaction, $F(21, 371) = 0.78, p = 0.75$, were significant. *T*-tests were again performed on these error data to assess transfer effect accuracy differences. None of the transfer effects were significant both during the training phase (NoSwitch, $t(10) = 0.49, p = 0.32$; Spatial/Direct, $t(16) = 1.09, p = 0.16$; Spatial/Indirect, $t(13) = 0.38, p = 0.36$; and Digits/Indirect, $t(14) = 0.94, p = 0.36$) and during the testing phase (NoSwitch, $t(10) = -$

0.96, $p = 0.18$; Spatial/Direct, $t(16) = -0.70$, $p = 0.25$; Spatial/Indirect, $t(13) = -1.01$, $p = 0.17$; and Digits/Indirect, $t(14) = 0.10$, $p = 0.46$.

3.3.2.2 Discussion

When only those participants without considerable explicit knowledge of the sequence were considered, testing phase differences began to emerge. Although only the Spatial/Direct and Spatial/Indirect groups demonstrated significant sequence knowledge during the training phase, RT trends for the other two groups were in the direction of sequence learning and there were no significant group differences among the four groups. These data indicate that all groups at least partially learned the sequence during the training phase. A power analysis revealed that training phase transfer effect power was again very poor (0.13) and it is possible that this lack of power is responsible for the lack of significant training phase transfer effects. At test, group differences were apparent. The NoSwitch and Digit/Indirect groups showed RTs in the direction of sequence knowledge, evidence that sequence knowledge transferred from the training to the testing phase. When only the implicit learners were considered, testing phase power much improved (0.68), but this testing phase power was still not very good.

3.3.3 Training Phase Learners

3.3.3.1 Results

3.3.3.1.1 Excluded Participants

As in Experiment 1, the purest method for identifying what is learned during implicit sequence learning is to consider only those participants who showed a transfer effect (evidence for learning) during the training phase. Four, five, four and seven participants in

the NoSwitch, Spatial/Direct, Spatial/Indirect and Digits/Indirect groups respectively were thus removed.

3.3.3.1.2 Reaction Times

Mean data were again analyzed with a two-way ANOVA with a between-subjects variable for Group (NoSwitch, Spatial/Direct, Spatial/Indirect, Digits/Indirect) and a within-subjects variable for Block (2-9). The test for sphericity was significant ($p < 0.001$) and the Huyhn-Feldt adjustment was used. There was a significant main effect of Block, $F(4.9, 162.8) = 27.60, p < 0.001$. The main effect of Group was not significant, $F(3, 33) = 0.86, p = 0.47$, nor was the Block x Group interaction, $F(14.8, 162.8) = 1.27, p = 0.23$. These data are plotted in Figure 15.

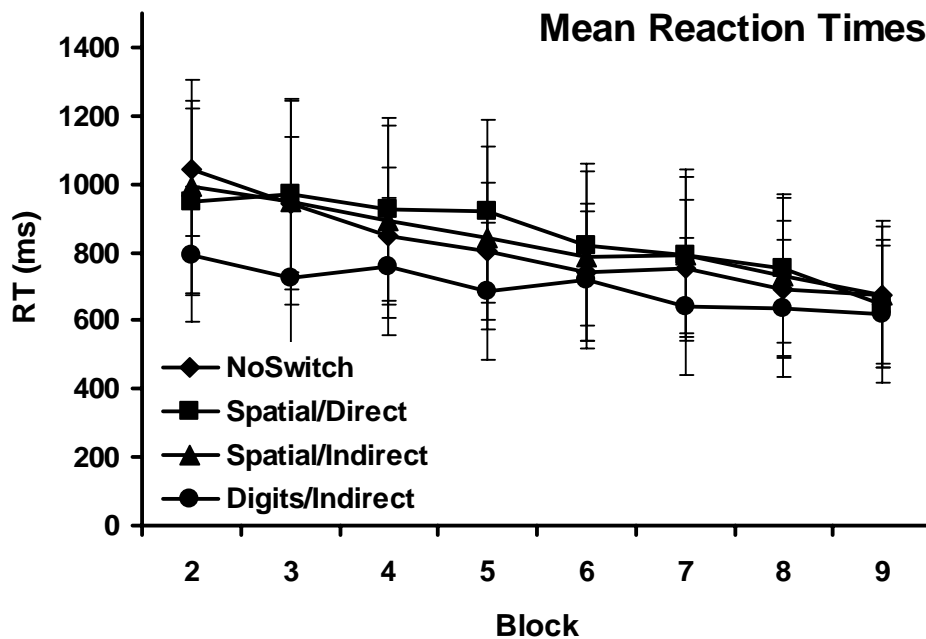


Figure 15. Training Phase Mean Reaction Times (Training Phase Learners)
Mean RTs across sequenced Blocks 2-7 for all three groups.

3.3.3.1.3 Training Phase Transfer Effect

Training phase transfer effects were calculated and one-tail t -tests were performed. These data are plotted in Figure 16. This time, the training phase transfer effect was statistically significant or nearly significant for all of the groups: NoSwitch, $t(6) = 1.77, p = 0.06$; Spatial/Direct, $t(11) = 3.91, p < 0.01$; Spatial/Indirect, $t(9) = 3.43, p < 0.01$; and Digits/Indirect, $t(7) = 3.62, p < 0.01$. A Structure by Group ANOVA was performed on the transfer data. The main effect of Structure, $F(1, 33) = 35.24, p < 0.001$, was significant. Neither the main effect of Group, $F(3, 33) = 0.17, p = 0.92$, nor the Structure x Group interaction, $F(3, 33) = 0.42, p = 0.74$, were statistically significant.

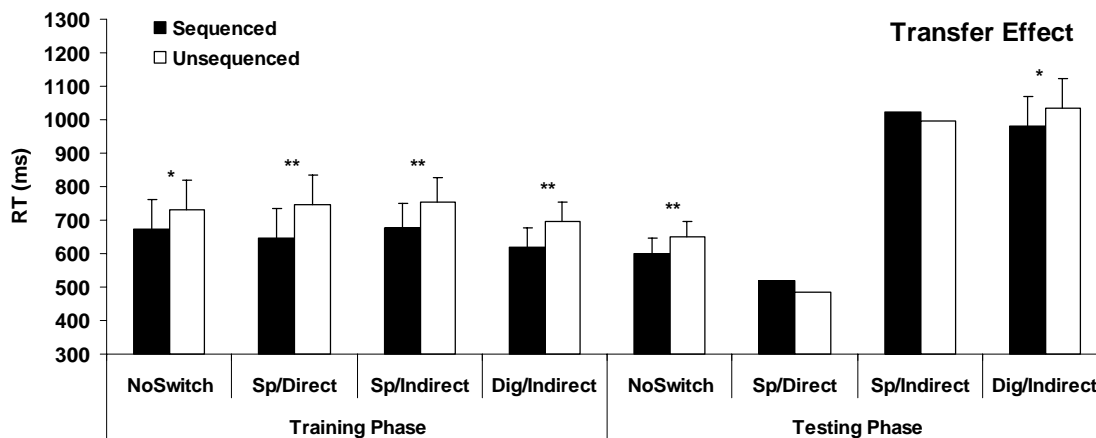


Figure 16. Training and Testing Phase Transfer Effects (Training Phase Learners) Mean RTs for the transfer effect in both the training and testing phases in Experiment 1. Means are presented for each of the three experimental conditions (NoSwitch, Spatial/Direct, Spatial/Indirect, Digits/Indirect). ** $p < 0.05$, * $p < 0.10$.

3.3.3.1.4 Testing Phase Transfer Effect

Testing phase transfer effects were calculated for these participants (Figure 16). As in the previous two analyses, both the Spatial/Direct and Spatial/Indirect groups showed RT trends in the opposite direction as is predicted by sequence learning. Statistical tests were not

conducted for these groups. The testing phase transfer effect was significant for the NoSwitch group, $t(6) = 2.75, p < 0.05$, and approached statistical significance for the Digits/Indirect group, $t(7) = 1.81, p = 0.06$. A Structure by Group ANOVA was conducted on the testing phase transfer data. The main effect of Structure, $F(1, 33) = 0.59, p = 0.45$, was not statistically significant. However, both the main effect of Group, $F(3, 33) = 14.59, p < 0.001$, and the Structure x Group interaction, $F(3, 33) = 3.41, p < 0.05$, were significant.

3.3.3.1.5 Error Rates

Mean error rates were 1.7 %, 2.7%, 3.9% and 4.7% for the NoSwitch, Spatial/Direct, Spatial/Indirect and Digits Hard groups respectively. Arcsine transformed data were again submitted to the same two-way ANOVA as in the previous error analysis. The test for sphericity was significant ($p < 0.05$) and the Huyhn-Feldt adjustment was used to correct the degrees of freedom. Neither the main effect of Block, $F(6.9, 227.7) = 1.36, p = 0.22$, nor the Block x Group interaction, $F(20.7, 227.7) = 1.31, p = 0.17$, were significant. The main effect of Group, $F(3, 33) = 3.85, p < 0.05$, was significant. Post Hoc analyses revealed the NoSwitch group was significantly more accurate than the Digits/Indirect ($p < 0.05$). When transfer effects were calculated on the error data, none of the groups showed significant error differences between the sequenced and unsequenced blocks during the training or testing phases. Training phase: NoSwitch, $t(6) = 0.76, p = 0.24$; Spatial/Direct, $t(11) = 1.23, p = 0.12$; Spatial/Indirect, $t(9) = 0.47, p = 0.33$; and Digits/Indirect, $t(7) = 0.97, p = 0.18$. Testing phase: NoSwitch, $t(6) = -0.27, p = 0.39$; Spatial/Direct, $t(11) = -1.12, p = 0.14$; Spatial/Indirect, $t(9) = -0.69, p = 0.25$; and Digits/Indirect, $t(7) = 0.61, p = 0.28$.

3.3.3.2 Discussion

When all participants and even when only the participants without explicit knowledge of the sequence were considered, statistical analyses did not provide a clear picture of what kind of sequence knowledge is transferred from the training to testing phase. However, when only the participants who did not demonstrate explicit knowledge of the sequence, but were faster on sequenced Block 9 compared to unsequenced Block 10 were considered, trends in the data appear. Despite the fact a power analysis revealed that power for detecting significant transfer effect data during the training phase was very low (0.13), significant or near significant transfer effects were calculated for all four groups. Though the testing phase power analysis indicated that power was still not ideal (0.76), the NoSwitch group demonstrated a significant transfer effect and this effect was nearly significant for the Digits/Indirect group. Transfer effect RTs for the remaining two groups did not demonstrate even a trend toward significance. These data indicate that sequence knowledge was transferred from the training to the testing phase only for the NoSwitch and Digits/Indirect.

3.4 Experiment 2 Conclusions

As previously noted, the response-based, stimulus-based and S-R rule-based theories of sequence learning each make different predictions concerning the outcome of Experiment 2 (Table 2). The response-based theory (e.g., Bischoff-Grethe, Geodert, Willingham, & Grafton, 2004; Willingham, 1999; Willingham, Wells, Farrell, & Stemwedel, 2000) asserts that when an individual learns a sequence the response locations are learned and also that there is a motor component to sequence learning. This theory would predict that none of the groups making verbal responses should demonstrate significant sequence learning because the response changes from the training phase to the testing phase.

The stimulus-based theory (e.g., Clegg, 2005; Cohen, Ivry, & Keele, 1990; Grafton, Salidis, & Willingham, 2001; Howard, Mutter, & Howard, 1992; Keele, Jennings, Jones, Caulton, & Cohen, 1995; Mayr, 1996; Verwey & Clegg, 2005) would make different predictions. Keele, Jennings, Jones, Caulton, and Cohen (1995), proponents of the theory, have demonstrated that sequence learning transfers from manual to verbal responses, so the changing the response modality should not affect sequence learning. This theory would thus predict significant transfer effects at test for the Spatial/Direct and Spatial/Indirect groups for which the stimuli stay the same during training and at test. It, however, would predict that the Digits/Indirect group would not show a significant transfer effect because the stimulus changed.

The S-R rule theory of sequence learning would make different predictions than both of these previous accounts. During the testing phase, this theory would predict significant transfer block effects for both the Spatial/Indirect and the Digits/Indirect groups. In these groups, S-R rules do not change from the training to the testing phase and thus learning should not be disrupted. If learning a sequence means learning a series of S-R rules, changing the S-R rules should result in no transfer of the learned sequence. Therefore, it is not likely that proponents of the S-R rule theory would expect to see significant sequence learning in the Spatial/Direct condition where the S-R rules have been altered dramatically.

Data from Experiment 2 are not exactly consistent with any of these predictions (Table 3). The discussion from this point on concerns only the data from those participants who demonstrated implicit sequence knowledge during the training phase of the experiment (the third analysis). The NoSwitch group, in which neither the stimulus sequence nor the response sequence nor the S-R rules were altered from training to test, demonstrated a

significant testing phase transfer effect. These results are consistent with all three theories of sequence learning. Similarly, the transfer effect approached significance, despite the low power, for the Digits/Indirect group. This finding is consistent only with the S-R rule-based account. The testing phase transfer effect was not significant for the Spatial/Direct group, which is also consistent with the response-based and S-R rule-based theories, but not the stimulus-based theory. And finally, the transfer effect was not significant for the Spatial/Indirect group, a finding inconsistent with both the perceptual and S-R rule theories, but consistent with the response-based theory.

Table 3. Experiment 2 Results Compared to Theory Predictions

		Theory			
		Perceptual	Response Location	S-R Rule	Results
	Control	Yes	Yes	Yes	Yes
Group	Spatial/Indirect	Yes	No	Yes	No
	Spatial/Direct	Yes	No	No	No
	Digits/Indirect	No	No	Yes	Yes

Each of the three theories of sequence learning (Learning is perceptual, learning is based on response locations and learning is contingent on S-R rules) make separate predications for whether or not learning will be demonstrated in the testing phase for each of the three theories. Here the predicted results are compared to the actual results from Experiment 2.

The combination of results from the Spatial/Indirect and Digits/Indirect groups are surprising for a number of reasons. The data from the Spatial/Indirect groups are seemingly inconsistent with the predictions of any of the currently available theories concerning the locus of sequence learning, save the response location theory; this theory predicts that when verbal responses are made at test, sequence knowledge retrieval will not occur. However, we know that it is not the nature of the verbal response at the root of the discord because

significant testing phase sequence learning was demonstrated by the Digits/Indirect group which used an identical verbal response mapping.

Additionally, these results are surprising because several researchers have previously demonstrated that sequence learning is effector independent (A. Cohen, Ivry, & Keele, 1990; Keele, Jennings, Jones, Caulton, & Cohen, 1995; Verwey & Clegg, 2005). However, in Experiment 2, when only the response modality was altered (Spatial/Indirect group), sequence learning did not transfer to the testing phase. It is possible that there are differences between changing effector (e.g., from finger to arm) and changing response modality (e.g., from manual to verbal), however, Keele, Jennings, Jones, Caulton, and Cohen (1995) have shown that sequence knowledge can indeed transfer across response modalities, so this is unlikely.

Keele, Jennings, Jones, Caulton, and Cohen (1995) demonstrated that sequence knowledge can at least partially transfer from a training phase in which manual responses were made (press the left, middle or right button) to a testing phase in which similar verbal responses were made (say “left,” “middle” or “right”). Marked differences between the Keele procedure and the current procedure are that the Keele procedure used three rather than four possible response locations, their sequences were considerably shorter (five vs. twelve-position sequence), a direct mapping was used, and during their experiment the SRT task and a secondary go/no go task were performed simultaneously. Certainly the structure of the Keele sequences was less complex than that of the current study; however, the addition of a secondary task has been shown to increase the difficulty of the task and even impair sequence learning (e.g., A. Cohen, Ivry, & Keele, 1990; Curran & Keele, 1993; Frensch, Buchner, & Lin, 1994; Nissen & Bullemer, 1987). So, despite the differences between these

two experiments, it is still surprising that the results would be so completely incompatible with each other. Keele and colleagues showed that during the testing phase, participants were faster on sequenced blocks than unsequenced blocks, whereas in the current experiment, the data reveal that sequenced blocks were not faster, and were perhaps even slower than unsequenced blocks. These data are completely unexpected and do not fit neatly into the current state of the literature.

3.4.1 Limitations

There are a few limitations of Experiment 2 that need to be discussed. First, power was quite low in Experiment 2 (0.13-0.76) and it is possible that the lack of significant transfer effect in both the Spatial/Direct and Spatial/Indirect groups was not a true null result, but rather a lack of sufficient power for detecting transfer effect differences. However, this is unlikely. It is important to remember that the overall RT trends for both the Spatial/Direct and Spatial/Indirect groups were in the opposite direction of an effect of sequence learning. Thirteen of the nineteen Spatial/Direct participants (68%) and ten of the seventeen Spatial/Indirect participants (59%) showed this pattern (sequenced block RTs slower than unsequenced block RTs). Thus, it is unlikely that increasing power would change these results.

An additional limitation to Experiment 2 was the large number of participants who either demonstrated high levels of explicit knowledge and/or failed to learn the sequence during the training phase: NoSwitch (61%), Spatial/Direct (37%), Spatial/Indirect (41%) and Digits/Indirect (56%). These results are surprising and it is not obvious why this occurred. Numerous similar SRT studies have been conducted and none reported large numbers of

participants who either learned the sequence explicitly or failed to learn the sequence during the training phase.

CHAPTER 4: GENERAL DISCUSSION

4.1 Overview

The present studies sought to evaluate the role of S-R rules in sequence learning. The results of Experiment 1 provided support for the idea that in the SRT task, participants are able to learn a sequence because they have acquired knowledge of the rules that bind the stimulus to the response. These data demonstrated that sequence learning can be neither purely stimulus-based nor purely response-based. This finding is important because it offers a new interpretation of sequence learning data and has the ability to explain the discrepancies between perceptual and motoric accounts. When previously reported findings supporting both the perceptual and motoric accounts are reconceptualized in an S-R rule framework, the results can be easily described. This idea is further discussed in the following section.

At first glance, the results of Experiment 2 might seem inconsistent with the S-R rule theory of sequence learning. However, it is important to note that only one of the group's data is, in fact, inconsistent. Sequence knowledge in the NoSwitch group, in which nothing changed from the training to the testing phase, remained intact during the testing phase. The same is true of the Digits/Indirect group in which both the stimulus type and the response modality were altered, but the S-R rules remained the same. For the Spatial/Direct group, the S-R rules completely changed from training to test and there was no evidence of sequence knowledge after the mapping change was implemented. Therefore, it is only the data from the Spatial/Indirect group do not adhere to the predictions of the S-R rule-based theory outlined in the introduction of Experiment 2.

However, these data might be explained if we consider Duncan's (1977) work on S-R rules. Duncan suggested that performance on choice RT tasks is contingent both by "whether individual stimuli and responses 'obviously correspond' [...and] by whether S-R relationships are the same in all the S-R pairs of the task" (Duncan, 1977). Consider, for a moment the Digits/Indirect and the Spatial/Indirect groups. Both groups were trained on the sequence with spatial stimuli and manual responses for 10 blocks and 960 trials. After these 10 training blocks, performance was very good and participants in both groups were responding with less than 5% errors. It is reasonable to conclude that after the practice session, there was an obvious learned correspondence between the required manual response and a given spatial stimulus. The Digits/Indirect group was trained that when a spatial stimulus was presented, a manual response was to be made and when a digit stimulus was presented a verbal response was to be made. Thus when a stimulus was presented, there was no ambiguity as to which type of response to make. However, the Spatial/Indirect group was trained to make both verbal and manual responses to the spatial stimulus. Thus, it is likely that during the testing phase both the well-practiced manual response and the instructed verbal response were simultaneously activated resulting in response competition (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Carter et al., 1998; J. D. Cohen, Dunbar, & McClelland, 1990). Participants made the correct verbal response only after the online monitoring mechanism detected the response competition and sent a control signal to adjust the response (Botvinick, Braver, Barch, Carter, & Cohen, 2001; Carter et al., 1998). Perhaps this processes of resolving response conflict obscured the benefit of having learned the sequence. This could also explain why testing phase transfer effects in the Keele study (Keele, Jennings, Jones, Caulton, & Cohen, 1995) were only about half as large for

participants who switched response modalities compared to participants who always made verbal responses.

4.2 Other Theories Explained by the S-R Rule Theory

Studies that report that sequence learning is effector-independent (A. Cohen, Ivry, & Keele, 1990; Keele, Jennings, Jones, Caulton, & Cohen, 1995; Verwey & Clegg, 2005) can easily be explained in an S-R rule framework. When participants learn a sequence with, for example, three-finger responses, they learn a set of S-R rules. When knowledge of the sequence is tested with, for example, one-finger responses, the S-R rules do not change. The effector changes, but this is not a sufficient alteration to disrupt the learned S-R rules. The same response is made to the same stimuli; just the mode of response is different. Similarly, when participants learn a sequence with one hand and then they switch to the other hand, this switch does not require a new set of S-R rules but only a transformation of the previously learned rules; though the specific S-R associations have changed, the general S-R rules are the same.

This conceptualization of S-R rules can provide an explanation for why various studies in the sequence learning literature report transfer or sequence learning to new effectors and new mappings. Alterations like changing effector (A. Cohen, Ivry, & Keele, 1990; Keele, Jennings, Jones, Caulton, & Cohen, 1995), switching hands (Verwey & Clegg, 2005), shifting responses one position to the left or right (Bischoff-Grethe, Geodert, Willingham, & Grafton, 2004; Willingham, 1999), changing response modalities (Keele, Jennings, Jones, Caulton, & Cohen, 1995) or using a mirror image of the learned S-R mapping (Deroost & Soetens, 2006; Grafton, Salidis, & Willingham, 2001) do not require a new set of S-R rules, but merely a transformation of the previously learned rules. When

there is a transformation of one set of S-R associations to another, the S-R rules theory predicts sequence learning.

S-R rule theory can also explain the results obtained by advocates of the response-based theory of sequence learning. Willingham (1999, Experiment 1) reported when participants only watch the series of stimuli, learning does not occur; but when participants respond to said stimuli, they learn the sequence. According to the S-R rule account, participants who only observe the sequence do not learn because S-R rules are not learned during observation (provided that the experimental design does not permit eye movements), whereas S-R rules are learned when responses are made. Similarly, Willingham, Wells, Farrell, and Stemwedel (2000, Experiment 1) conducted an SRT experiment in which participants responded to stimuli arranged in a lopsided diamond pattern using one of two keyboards, one in which the buttons were arranged in a diamond and the other in which they were arranged in a straight line. Participants used the index finger of their dominant hand to make all responses. Willingham and colleagues reported that participants who learned a sequence using one keyboard and then switched to the other keyboard show no evidence of sequence learning. The S-R rule account says that there are no correspondences between the S-R rules required to perform the task with the straight-line keyboard and the S-R rules required to perform the task with the diamond keyboard. The tasks are too dissimilar and therefore a mere transformation of the S-R rules originally learned is not sufficient to transfer sequence knowledge acquired during training.

4.3 Future Direction

The proposed theory that sequence learning is contingent on S-R rules raises other interesting questions. There are a number of other studies that can be conducted to

systematically investigate the role of S-R rules in sequence learning. Functional imaging techniques can be used to investigate how brain regions mediating these trial level processes (e.g., prefrontal, premotor, and parietal cortices) and those mediating cross-trial performance (e.g., medial temporal as well as prefrontal and premotor cortices) interact to support task performance on a trial-by-trial basis and the learning of cross-trial associations (Hazeltine, Grafton, & Ivry, 1997; Poldrack & Rodriguez, 2003; Schendan, Searl, Melrose, & Stern, 2003). These regions believed to be important for acquiring and using S-R rules have also been reported in the sequence learning imaging literature (Hazeltine, Grafton, & Ivry, 1997; Schendan, Searl, Melrose, & Stern, 2003). Further investigation is necessary to explore the direct comparison between the role of these regions in task performance (e.g., learning incompatible mappings) and sequence learning (learning a sequence). An interesting question asks whether these structures implicated in the learning of S-R rules in human performance studies are sufficient to support sequence learning or if other regions are important for and specific to this activity.

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