PURE PERCEPTUAL-BASED SEQUENCE LEARNING

by

Gilbert Remillard

A Thesis

submitted to the Faculty of Graduate Studies

in partial fulfillment of the requirements for the Degree of

Doctor of Philosophy

Department of Psychology

University of Manitoba

Winnipeg Manitoba Canada

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PURE PERCEPTUAL-BASED SEQUENCE LEARNING

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GILBERT REMILLARD

A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University

of Manitoba in partial fulfillment of the requirements of the degree

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Pure Perceptual-Based Sequence Learning

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TABLE OF CONTENTS

Page

Appendices

Figures

Tables

ABSTRACT

The present study examined implicit learning of a sequence of target locations when the sequence is uncorrelated with a sequence of responses and target location is not relevant for responding (pure perceptual-based sequence learning). Contrary to current hypotheses of implicit sequence learning, which suggest that such learning is not possible, the results of the present study show that pure perceptual-based learning is possible. Specifically, the results show that people can implicitly learn first-order transition probabilities embedded in a probabilistic sequence of target locations when the sequence is uncorrelated with a sequence of motor responses and target location is not relevant for responding. The results further show that the mechanism underlying such learning affords processing of information at anticipated target locations and that learning is mostly limited to first-order probabilities. Learning of second-order transition probabilities is considerably impaired relative to learning of first-order probabilities. In addition to pure perceptual-based learning, priming associated with the repetition of bigrams was examined. Parallels between learning and priming suggest that both may be subserved by similar mechanisms.

INTRODUCTION

Implicit learning is currently the focus of considerable research. Although there is no single, agreed-upon definition of implicit learning, most definitions include the characterization that implicit learning is learning that is *not* the result of conscious, intentional processes (e.g., Berry, 1994; Cleeremans, Destrebecqz, & Boyer, 1998; Frensch, 1998; Perruchet, 1994; Perruchet & Vinter, 1998; Reber, 1989; Seger, 1994, 1998; Stadler & Roediger, 1998). This contrasts with explicit learning which is learning that is the result of conscious processes. The distinction between implicit and explicit learning suggests the existence of different learning mechanisms.

A popular paradigm for studying implicit learning is sequence learning. Implicit sequence learning is learning about a sequence of events that is not the result of conscious processes and has been studied using the serial reaction time (SRT) task (Nissen & Bullemer, 1987). On each trial of the SRT task, a target appears at any one of a number of locations on the computer screen and participants press, as quickly as possible, the key corresponding to the location of the target. The target then disappears and a few hundred milliseconds later reappears in a different location.

In most applications of the SRT task, the sequence of target locations is deterministic (i.e., it repeats following a number of trials). Sequence learning occurs when the repeating sequence of target locations elicits shorter reaction times than a random sequence of target locations. In other applications of the SRT task, the sequence of target locations is probabilistic (i.e., the next target location is a probabilistic function of previous locations). Sequence learning occurs when, given previous target locations, more probable succeeding locations elicit shorter reaction times than less probable

succeeding locations.

Establishing Implicit Sequence Learning

Measuring Sequence Awareness

Almost all SRT task studies establish implicit sequence learning by measuring

participants' awareness of the sequence of target locations following training. Sequence

learning that is explicit (i.e., the result of conscious processes) would presumably lead to

an awareness of the sequence of target locations. Therefore, a lack of awareness of the

sequence of target locations would suggest that sequence learning was implicit (i.e., not

the result of conscious processes). Using this approach, a number of SRT task studies

have provided evidence for implicit sequence learning. Participants in these studies learn

the sequence of target locations, as assessed by reaction time, and yet have no awareness

of the sequence as assessed by free-recall, cued-recall, or recognition tasks (e.g.,

Cleeremans & McClelland, 1991; Curran & Keele, 1993; Lewicki, Hill, & Bizot, 1988;

McDowall, Lustig, & Parkin, 1995; Reed & Johnson, 1994; Remillard & Clark, 2001;

Stadler, 1989, 1993, 1995; Willingham, Nissen, & Bullemer, 1989).

However, the evidence for no awareness of the sequence of target locations has

been criticized on a number of grounds. First, free-recall tasks are insensitive measures of

sequence awareness because they provide almost no retrieval cues and because sequence

knowledge that is conscious but held with low confidence may not be reported (Dienes &

Berry, 1997; Shanks & Johnstone, 1998; Shanks & St. John, 1994; Stadler, 1997).

Second, a number of SRT task studies have used a cued-recall task called the

generate task. On each trial in the generate task, the target appears in a location and

participants predict the next location in the sequence. Following a prediction, the target

moves to the next location in the sequence. It has been argued that the generate task may be a relatively insensitive measure of sequence awareness because erroneous predictions and the time it takes to make predictions may interfere with the maintenance of earlier target locations in working memory (Perruchet & Amorin, 1992; Perruchet & Gallego, 1993; but see Cohen & Curran, 1993).

Third, SRT task studies sometimes show that participants, on average, do have awareness of the sequence. A common response in such circumstances is to consider participants who scored low on the measure of sequence awareness and show that they learned the sequence of target locations as assessed by reaction times. However, low scores do not necessarily imply a lack of sequence awareness. They may simply reflect the measure's less than perfect reliability (Perruchet & Amorin, 1992; Perruchet & Gallego, 1993; Shanks & Johnstone, 1999, pp. 1442-1443) or its less than perfect sensitivity.

Finally, sequences in SRT task studies usually contain a number of constraints, any of which may be learned. For example, given the sequence 4-2-3-1-3-2-4-3-2-1, where numbers represent target locations, participants may learn which locations are most likely to follow the preceding location (e.g., 2 is more likely than 1 to follow 3), which locations are most likely to follow the preceding two locations (e.g., 3 always follows 4-2), or which locations are most likely to occur on trial $t + 2$ given the location on trial t (e.g., 3 and 2 but not 1 can occur on trial $t + 2$ if 4 occurs on trial t). Most SRT task studies fail to identify which constraints have been learned. This has been a major criticism of SRT task studies because without knowing what was learned, one cannot be certain that measures of sequence awareness assessed awareness of the information

learned (Jackson & Jackson, 1995; Perruchet, Gallego, & Savy, 1990; Shanks, Green, & Kolodny, 1994; Shanks & St. John, 1994).

Thus according to critics, a valid demonstration that participants have no awareness of the sequence of target locations would be chance performance on a measure of sequence awareness that (a) assesses awareness of the sequential contraints actually learned during training, (b) implements forced-choice responding so that sequence knowledge that is conscious but held with low confidence would be reported, and (c) reinstates many of the cues present during training. Because few SRT task studies meet these criteria, critics have concluded that there has been no convincing demonstration that participants can be unaware of the sequence of target locations (but see Remillard & Clark, 2001).

As a final note, if a measure reveals awareness of the sequence of target locations, then this does not necessarily imply that sequence learning was not implicit. Sequence learning may have been implicit but upon reflection following training, participants became aware of the sequence of target locations. Alternatively, awareness of the sequence of target locations may have been the result of explicit sequence learning that occurred in parallel with implicit sequence learning (Curran & Keele, 1993; Willingham & Goedert-Eschmann, 1999; also see Marsolek & Field, 1999).

Manipulating Availability of Conscious Processes

If sequence learning is explicit, then manipulations that affect the availability of conscious processes to the SRT task should also affect sequence learning. Therefore, if such manipulations do not affect sequence learning, this would suggest that sequence learning was implicit.

One manipulation is to impose a secondary task (e.g., counting tones) on the primary SRT task. The secondary task presumably reduces the availability of conscious processes to the primary task. The addition of a secondary task has no effect on reaction time measures of sequence learning when the sequence of target locations is probabilistic (Cleeremans & Jimenez, 1998; Jimenez & Mendez, 1999; Schvaneveldt & Gomez, 1998) and has a negative effect when the sequence of target locations is deterministic (Cleeremans & Jimenez, 1998; Frensch, Buchner, & Lin, 1994; Frensch & Miner, 1994; Heuer & Schmidtke, 1996; Hsiao & Reber, 2001; Shanks & Channon, 2002; Stadler, 1995). The latter result does not necessarily imply that the learning of deterministic sequences is not implicit. Implicit and explicit sequence learning may occur in parallel and the secondary task affects explicit sequence learning (Curran & Keele, 1993; Willingham & Goedert-Eschmann, 1999; also see Marsolek & Field, 1999). Alternatively, sequence learning may be implicit and the secondary task either affects the expression of sequence learning (Frensch, Lin, & Buchner, 1998; Frensch, Wenke, & Runger, 1999; but see Shanks & Channon, 2002) or changes the structure/timing of the sequence in such a way that makes it more difficult to learn (Frensch et al., 1994; Rah, Reber, & Hsiao, 2000; Schmidtke & Heuer, 1997; Stadler, 1995).

Another manipulation is to inform participants prior to the SRT task that the sequence of target locations is structured and instruct them to try to learn the structure. Such a manipulation presumably increases the availability of conscious processes to the SRT task. Orienting participants to the sequential structure has no effect on reaction time measures of sequence learning when the sequence of target locations is probabilistic (Cleeremans & Jimenez, 1998; Jimenez, Mendez, & Cleeremans, 1996; also see Howard

& Howard, 2001) and has a positive effect when the sequence of target locations is deterministic (Cleeremans & Jimenez, 1998; Curran & Keele, 1993; Frensch & Miner, 1994). The latter result does not necessarily imply that the learning of deterministic sequences is not implicit. Implicit and explicit sequence learning may occur in parallel and the orienting manipulation affects explicit sequence learning (Curran & Keele, 1993; Willingham & Goedert-Eschmann, 1999; also see Marsolek & Field, 1999).

An interesting manipulation used by Cleeremans (1997; also see Jimenez & Mendez, 2001) was to provide a cue on each trial of the SRT task indicating where the target might appear on the next trial. The cue was valid in one condition (i.e., correct 80% of the time) and invalid in another condition (i.e., correct 40% of the time). Cleeremans (1997) used a probabilistic sequence of target locations in which preceding target locations were less predictive of the next target location than the valid cue. Thus the valid cue, relative to the invalid cue, would presumably draw conscious processes and reduce the availability of conscious processes to learning of the sequence of target locations. Cue validity had little effect on reaction time measures of sequence learning.

In summary, manipulations that presumably affect the availability of conscious processes to the SRT task have no effect on reaction time measures of sequence learning when the sequence of target locations is probabilistic, but do have an effect when the sequence of target locations is deterministic. This suggests that learning of probabilistic sequences is mostly implicit and learning of deterministic sequences may be to some extent explicit (for further support of this conclusion using a digit-sequence entry task, see Marsolek & Field, 1999).

Probabilistic Versus Deterministic Sequences

The vast majority of SRT task studies have used deterministic sequences of target locations. Only a handful of studies have used probabilistic sequences. A number of considerations suggest that probabilistic sequences may be better suited for studying implicit sequence learning than deterministic sequences. First, as noted in the previous section, learning of probabilistic sequences may be mostly implicit, whereas learning of deterministic sequences may be to some extent explicit.

Second, probabilistic sequences allow for tighter control over the constraints learned by participants than deterministic sequences (e.g., Remillard & Clark, 2001). As noted earlier, this is important for accurately assessing awareness of the information learned. Using highly controlled probabilistic sequences of target locations, Remillard and Clark (2001) showed that participants learned first-, second-, and third-order transition probabilities.[1] Learning was implicit because performance on measures assessing awareness of the transition probabilities revealed that participants were not aware of the probabilities. These results further support the notion that learning of probabilistic sequences is mostly implicit.

Finally, there is evidence that when exposed to a deterministic sequence of target locations, people may learn probabilistic information (e.g., transition probabilities) embedded in the sequence. For example, sequences with higher internal transition probabilities (e.g., 2-4-2-3-1-2-3-4-2-3 where $P(2|1) = 1.0$, $P(3|2) = .75$, and so on) elicit shorter reaction times than sequences with lower internal transition probabilities (e.g., 2-4-2-3-1-2-1-4-1-3 where $P(2|1) = .33$, $P(3|2) = .33$, and so on) (Stadler, 1992; Stadler & Neely, 1997; also see Wenger & Carlson, 1996, Experiment 1). Also, for sequences of the form 1-2-3-2-4-3, reaction time on 2 following 1 and on 3 following 4, which have first-

order transition probabilities of 1.0, is shorter than that on other transitions, which have first-order probabilities of .5 (Curran & Keele, 1993, Experiment 2; Frensch et al., 1994). Cleeremans and Jimenez (1998) have proposed that implicit and explicit learning of deterministic sequences can occur simultaneously and involve, respectively, learning of transition probabilities and learning of serial position information (i.e., the exact order of target locations within the entire sequence or within chunks of the sequence). Thus understanding implicit learning of probabilistic sequences can help in understanding implicit learning of deterministic sequences.

Perceptual-Based Versus Response-Based Sequence Learning

In most applications of the SRT task, the sequence of target locations is correlated with the sequence of responses because participants must press the key corresponding to the location of the target. Consequently, participants may be learning a sequence of target locations (*perceptual-based learning*, for example, location 1 - location 3 - location 1 - location 2 - location 4), a sequence of response locations (*response-based learning*, for example, key 1 - key 3 - key 1 - key 2 - key 4), or a sequence of effector movements (*effector-based learning*, for example, finger 1 - finger 3 - finger 1 - finger 2 - finger 4).

Studies suggest that sequence learning is not effector-based. When participants are transferred from one set of effectors to another and the sequences of target and response locations remain the same, there is complete transfer of sequence knowledge (Cohen, Ivry, & Keele, 1990; Keele, Jennings, Jones, Caulton, & Cohen, 1995; Stadler, 1989; but see Heyes & Foster, 2002). Conversely, when the sequences of target and response locations are changed and the sequence of effector movements remains the same, there is little transfer of sequence knowledge (Willingham, Wells, Farrell, &

Stemwedel, 2000).

A recent study by Willingham (1999; also see Heyes & Foster, 2002; Willingham et al., 2000) suggests that sequence learning is primarily response-based. Willingham found little transfer of sequence knowledge when the sequences of response locations and effector movements were changed and the sequence of target locations remained the same. Conversely, there was considerable transfer of sequence knowledge when the sequence of target locations was changed and the sequences of response locations and effector movements remained the same. Assuming that sequence learning was not effector-based, the results suggest that sequence learning was primarily response-based.

In contrast, Keele et al. (1995) obtained evidence suggesting that sequence learning is to some extent perceptual-based. Keele et al. transferred participants from one set of effectors (three fingers pressing three keys) to another (verbal responses with no key presses) and maintained the sequence of target locations. Even though the sequences of response locations and effector movements were eliminated, there was transfer of sequence knowledge suggesting that sequence learning was to some extent perceptual-based. Unfortunately, Keele et al. did not examine how much of the sequence knowledge transferred and so how much of the sequence learning was response-based.

A study by Stadler (1989) suggests that sequence learning is primarily perceptual-based. Stadler transferred participants from one set of target locations (the four corners of an imaginary square) to another (the corners of a much smaller square) and found no evidence of transfer of sequence knowledge in spite of the fact that the sequences of response locations and effector movements remained the same.

Thus three studies suggest that sequence learning is primarily response-based

(Heyes & Foster, 2002; Willingham, 1999; Willingham et al., 2000) and two studies

suggest that sequence learning is to some extent perceptual-based (Keele et al., 1995;

Stadler, 1989). Relative to the latter set of studies, two of the three studies in the former

set used a less compatible mapping between target location and response location during

training. For some unknown reason, this may have hindered perceptual-based learning or

promoted response-based learning. Alternatively, there may have been perceptual-based

learning during training in the two studies but the transfer tasks, which introduced a new

mapping between target and response location, may have hindered the expression of such

learning. Ziessler (1994, p. 32) noted that "the transfer task is a new task for the subjects,

which has its own requirements. A failure of transfer of the stimulus sequence or of the

response sequence does not necessarily mean that they were unimportant for the

sequential-pattern learning in the training task." Clearly, more work is required to

establish the extent of perceptual- and response-based learning when sequences of target

and response locations are correlated.

Studies using nontransfer approaches suggest that sequence learning can be

perceptual-based when there is no correlated sequence of response locations. For

example, participants in a study by Hartman, Knopman, and Nissen (1989) responded

verbally to a repeating sequence of centrally presented words (verbal/words condition),

verbally to a repeating sequence of target locations (verbal/locations condition), or with

keypresses to a repeating sequence of centrally presented words (keypress/words

condition). Even though the structure of the repeating sequence of verbal responses was

the same in the verbal/words and verbal/locations conditions, sequence learning was

greater in the latter condition. This suggests the sequence of target locations was learned

in the verbal/locations condition (perceptual-based learning). In a similar fashion, the structure of the repeating sequence of centrally presented words was the same in the verbal/words and keypress/words conditions but sequence learning was greater in the latter condition. This suggests the sequence of keypresses was learned in the keypress/words condition (response-based learning).

A study by Baldwin and Kutas (1997; also see Vakil, Kahan, Huberman, & Osimani, 2000) also yielded evidence for perceptual-based learning in the absence of a correlated sequence of response locations. Baldwin and Kutas used nine target locations arranged in a 3x3 array and a single response key. The sequence of target locations was probabilistic in that given the previous two target locations, some locations were more probable successors than others. Participants monitored the movement of the target and pressed the key whenever a specific motion was detected. The motion to be detected (a horizontal, vertical, diagonal, or knight's move) varied across blocks of trials. Reaction times were shorter when motions occurred on high probability transitions than when they occurred on low probability transitions indicating perceptual-based learning.

Pure Perceptual-Based Sequence Learning

The majority of the preceding studies suggest that perceptual-based learning is possible. However, participants in those studies responded (verbally or with keypresses) to target location or to target location transitions. Some investigators have examined whether *pure perceptual-based learning* is possible--that is, whether perceptual-based learning is possible when the sequence of target locations is uncorrelated with the sequence of responses and target location is not relevant for responding. For example, Willingham et al. (1989) had participants respond to the color of the target rather than its

location. On each trial, a colored target appeared at one of four locations. The sequence of

target colors was random, whereas the sequence of target locations repeated. Thus the

sequence of target locations was uncorrelated with the sequence of responses. Reaction

times revealed no learning of the sequence of target locations. The result suggests that

pure perceptual-based learning is not possible.

Consistent with this interpretation, Baldwin and Kutas (1997, p. 80), in a slight

procedural change to the motion-detection experiment outlined earlier, had participants

respond to a single motion (a knight's move) throughout training, rather than vary the

motion to be detected across training blocks. At the end of training, test blocks were

introduced that required responding to all four motion types (horizontal, vertical,

diagonal, or knight's moves). Shorter reaction times on high than low probability

transitions emerged only in those test blocks that required responding to knight's moves.

No such differences were observed in the test blocks that required responding to other

motion types. Thus, even though participants had to attend to all transitions to

successfully perform the knight's move discrimination during training, they seemed to

learn only about the high probability transitions that required responding (i.e., that

produced knight's moves). High probability transitions that were not relevant for

responding during training (i.e., that produced horizontal, vertical, or diagonal moves)

were not learned.

Using a different approach to try to obtain evidence for pure perceptual-based

learning, Howard, Mutter, and Howard (1992; also see Heyes & Foster, 2002) had

participants initially observe a repeating sequence of target locations without making any

kind of response, and then subsequently respond to the location of the target. Reaction

times revealed learning of the sequence of target locations through observation. However, there was considerable awareness of the sequence of target locations in the Howard et al. (1992) study. Consequently, learning during observation may have been explicit rather than implicit. In a similar study, Willingham (1999; also see Kelly & Burton, 2001) found little evidence for learning of the sequence of target locations during observation after excluding participants with high levels of awareness of the sequence. However, Seger (1996, 1997) did find evidence for learning during observation after excluding participants with high levels of awareness. The Seger (1996, 1997) and Willingham (1999) studies were similar and so it is not obvious why they produced different results. Given that observation tends to produce higher than usual levels of sequence awareness (but see Kelly & Burton, 2001) and that there are no constraints on what participants do during the observation period, observation studies may not be the best approach to examine pure perceptual-based learning.

The best evidence against pure perceptual-based learning has been Willingham et al.'s (1989) study where participants responded to target color rather than target location. Willingham et al. used four horizontally arranged target locations with adjacent locations separated by 4.8 cm. A number of people have speculated that with such narrowly separated target locations, shifts of visuospatial attention or eye movements may not have been large enough to permit perceptual-based learning to develop (Jimenez & Mendez, 1999; Mayr, 1996; Willingham, 1999; Willingham et al., 2000) or to be detected if it did develop (Mayr, 1996).

Whatever the reason, distance between target locations may be an important factor. In their motion-detection experiment, Baldwin and Kutas (1997) used nine target

locations arranged in a square 3x3 array with side length of only 5.0 cm and found no

evidence for pure perceptual-based learning. Conversely, in a conceptual replication of

Willingham et al.'s (1989) target color experiment, Mayr (1996) used widely separated

target locations (the four corners of an imaginary square with side length of 22 cm) and

obtained evidence for pure perceptual-based learning. Finally, in another conceptual

replication of the Willingham et al. (1989) study, Helmuth, Mayr, and Daum (2000)

obtained evidence for pure perceptual-based learning, but only when the target locations

(the four corners of an imaginary diamond with each corner being 6.7 degrees of visual

angle from a central fixation point) necessitated eye movements. No such evidence was

found when the target locations (each corner being 5.0 degrees of visual angle from

central fixation) did not require eye movements. Unfortunately, Helmuth et al. placed

participants in the eye movement condition only after they had been in the no eye

movement condition. Thus the results could be due to greater exposure to the repeating

sequence of target locations in the former than latter condition, rather than to differences

in the distance between target locations.

The Mayr (1996) and Helmuth et al. (2000) studies provide the best evidence to

date that perceptual-based learning is possible when the sequence of target locations is

uncorrelated with the sequence of responses and target location is not relevant for

responding. A demonstration of pure perceptual-based learning has important

implications for hypotheses of implicit sequence learning.

Implications for Hypotheses of Implicit Sequence Learning

According to a number of authors, responding motorically to events in a sequence

is critical for learning the sequence of events. For example, Ziessler (1994, 1998; Ziessler

& Nattkemper, 2001) has argued that response-effect learning is the major component of sequence learning. When exposed to a sequence of events, people learn to associate the response to the current event with the next event in the sequence because the next event is the "effect" of responding to the current event. Hoffman, Sebald, and Stocker (2001) have added that people will also learn to associate events in the sequence if distinct events are the "effect" of distinct responses. Nattkemper and Prinz (1997; also see Russeler, Hennighausen, & Rosler, 2001; Russeler & Rosler, 2000) have suggested that learning a sequence of events occurs at a motor level and not a perceptual level. In contrast, Kelly and Burton (2001, Experiment 2) have presented data suggesting that learning a sequence of events can occur at a perceptual level provided that events are responded to motorically. Finally, Willingham (1998, 1999; Willingham et al., 2000) has proposed that learning a sequence of spatial locations involves the creation of a representation of the sequence in egocentric space and that the creation of such a representation is possible only if motor responses are directed to the spatial locations.

Other authors have suggested that effortful (i.e., nonautomatic) processing of events in a sequence is critical for learning the sequence of events (Baldwin & Kutas, 1997; Hartman et al., 1989; Jimenez & Mendez, 1999; also see, Jiang & Chun, 2001). For example, Hartman et al. (1989) observed learning of a repeating sequence of words when participants semantically categorized the words (an effortful task), but not when they read the words (an automatic task).

Contrary to the preceding hypotheses, pure perceptual-based learning suggests that motoric responding to or effortful processing of events in a sequence is not necessary for learning the sequence of events. People apparently can learn a sequence of target

locations when target location is not relevant for responding--that is, when target location is not responded to motorically or processed effortfully.

The Role of Oculomotor Programming

One could argue that pure perceptual-based learning somehow involves oculomotor programming so that in actuality, target location is responded to motorically. This could be difficult to discount because the sudden appearance of a stimulus in the visual field, as occurs in the SRT task, may automatically program an eye movement towards the stimulus (Guitton, Buchtel, & Douglas, 1985; Ladavas, Zeloni, Zaccara, & Gangemi, 1997; Rafal, Calabresi, Brennan, & Sciolto, 1989; Rizzolatti, Riggio, & Sheliga, 1994; Theeuwes, Kramer, Hahn, & Irwin, 1998; Theeuwes, Kramer, Hahn, et al., 1999; Todd & Van Gelder, 1979). Thus, preventing oculomotor programming in the SRT task may be difficult to achieve.

However, a number of considerations, taken together, suggest pure perceptual-based learning is more likely to be associated with programming shifts of visuospatial attention than with oculomotor programming. First, eye movements are normally preceded by shifts of attention (Chelazzi, Biscaldi, Corbetta, et al., 1995; Deubel & Schneider, 1996; Godijn & Pratt, 2002; Hoffman & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser, 1995; Posner, 1980; Remington, 1980; Stelmach, Campsall, & Herdman, 1997, Experiment 2). Second, the mechanism for programming shifts of attention is independent of that for programming eye movements (Abrams & Pratt, 2000; Crawford & Muller, 1992; Deubel & Schneider, 1996; Deubel, Schneider, & Paprotta, 1998; Ditterich, Eggert, & Straube, 2000; Klein & Pontefact, 1994; Ladavas et al., 1997; Posner, 1980; Rafal et al., 1989; Remington, 1980; Reuter-Lorenz & Fendrich, 1992;

Shulman, 1984; Stelmach et al., 1997; for a contradictory view, however, see Rizzolatti

& Craighero, 1998; Rizzolatti et al., 1994). Finally, the sudden appearance of a stimulus

in the visual field, as occurs in the SRT task, automatically captures attention (Folk,

Remington, & Wright, 1994; Jonides, 1981; Jonides & Yantis, 1988; McCormick, 1997;

Muller & Rabbitt, 1989; Remington, Johnston, & Yantis, 1992). Thus it is reasonable to

assume that oculomotor programming is not necessary for pure perceptual-based learning

and that automatic orienting of visuospatial attention is sufficient.

The Current Study

Given the potential importance of pure perceptual-based learning for hypotheses

of implicit sequence learning, the current study sought to extend the results of Mayr

(1996) and Helmuth et al. (2000) described earlier and further characterize pure

perceptual-based learning. The current study had four goals. The first goal was to show

that pure perceptual-based learning is possible when the sequence of target locations is

probabilistic. Mayr (1996) and Helmuth et al. (2000) used deterministic sequences of

target locations. As noted earlier, learning of probabilistic sequences may be mostly

implicit, whereas learning of deterministic sequences may be to some extent explicit.

Indeed, participants in Mayr's (1996) study had, on average, significant awareness of the

sequence of target locations raising the possibility that sequence learning had been to

some extent explicit. A second advantage of probabilistic sequences over deterministic

sequences is that the former enable tighter control over the constraints learned by

participants than the latter, which is important for accurately assessing awareness of the

information learned. Thus observing pure perceptual-based learning with probabilistic

sequences of target locations and no awareness of the information learned would be

strong evidence that such learning can be implicit.

The second goal of the current study was to show that pure perceptual-based learning is possible when target locations are horizontally arranged and separated by relatively narrow distances. Mayr (1996) and Helmuth et al. (2000) used widely separated target locations arranged in two dimensions. It is not yet known whether pure perceptual-based learning is possible when target locations are much closer to one another and arranged along a single dimension.

In the current study, there were six horizontally arranged target locations with adjacent locations separated by 2.1 cm (Experiment 1), 1.1 cm (Experiments 2-4), or 0.5 cm (footnote 4). Thus the distance between the two end locations was shorter than that in Willingham et al. (1989) who used four horizontally arranged target locations with adjacent locations separated by 4.8 cm and found no evidence for pure perceptual-based learning. Participants responded to the target bigrams xo and ox with left and right key responses, respectively. Thus target location was not relevant for responding. The sequence of targets and hence responses was unstructured and independent of the sequence of target locations which was probabilistically structured. Given the preceding target locations, there was one high and one low probability transition (i.e., successor). Shorter reaction times on high than low probability transitions would indicate pure perceptual-based learning of the transition probabilities.

Given that pure perceptual-based learning might be difficult to detect with narrowly separated target locations, an approach was needed that had the potential to be sensitive to such learning if it did occur. The approach I used was based on an approach used by Goschke (1998, pp. 416-419; Goschke, Friederici, Kotz, & Kampen, 2001) for

studying implicit learning of a repeating sequence of auditorily presented letters. On each trial in Goschke's study, the four possible letters were displayed as a random letter string on a monitor (e.g., CDBA) and 500 ms later, a target letter was presented auditorily (e.g., "D"). Participants pressed the key corresponding to the location of the target letter in the letter string (e.g., in the case of "D", the key for location 2). Immediately after a response, the next trial began with another random letter string (e.g., BCDA). Reaction times decreased with training and increased when the sequence of auditorily presented letters became random. According to Goschke, participants located the anticipated target letter in the letter string during the 500-ms interval and prepared the response corresponding to its location in the string. This produced reaction time benefits which, when the sequence became random, disappeared and perhaps turned to costs as incorrect responses were prepared.

In the current study, sensitivity to learning of the transition probabilities was enhanced by allowing knowledge of the transition probabilities to produce substantial reaction time benefits and costs on high and low probability transitions, respectively. On a trial, the six target locations were marked with a random ordering of the bigrams xo and ox with the constraints that there were three of each bigram and that low and high probability transitions were marked with different bigrams. For example, if, given the target locations on preceding trials, locations 3 and 4 are the low and high probability transitions, respectively, then the bigram ordering might be "xo xo ox xo ox ox" with locations 3 and 4 marked with different bigrams. Four hundred milliseconds after the appearance of the bigram-ordering, a line appeared below either the bigram marking the low probability transition (e.g., location 3) or the bigram marking the high probability

transition (e.g., location 4). Participants pressed the key corresponding to the underlined target bigram (i.e., left key for xo and right key for ox). Immediately after a response, the next trial began with the appearance of another ordering of the bigrams xo and ox.

If participants learn that given the preceding target locations, location A is a more likely transition than location B then they might process, during the 400 ms interval between bigram-ordering and underlining of the target bigram, the bigram marking location A and prepare the corresponding response. This should produce a reaction time benefit if location A is underlined and a cost if location B, which is marked with a different bigram requiring a different response, is underlined.

Enhanced sensitivity to learning of the transition probabilities is contingent on processing, during the 400 ms interval, the bigram marking the high probability transition. This raises an interesting question. Does the mechanism underlying pure perceptual-based learning afford processing of information at an anticipated target location before the cue (i.e., underline) is presented at the location or does it afford processing only after the cue is presented but with increased efficiency? For example, if the mechanism is assumed to be a program for successive orientations of visuospatial attention (Posner & Rothbart, 1992), then the question might be whether an attentional shift to the anticipated target location is programmed and executed before the cue, or programmed before the cue but executed only after the cue. Mayr (1996, p. 359) raised a similar question when he noted that "Presumably, implicit learning of the spatial sequence either allowed participants to make anticipatory eye [or attentional] movements to correct locations or reduced the threshold for correct eye [or attentional] movements once the object appeared on the screen."

The third goal of the current study was to show that the mechanism underlying pure perceptual-based learning affords processing of information at an anticipated target location before the cue (i.e., underline) is presented. To this end, a second condition was introduced in which the six target locations were marked with the bigrams mn and nm rather than xo and ox. On a trial, the six target locations were marked with a random ordering of the bigrams mn and nm with the constraints that there were three of each bigram and that low and high probability transitions were marked with different bigrams (e.g., "mn nm nm mn mn nm" where locations 3 and 4 are the low and high probability transitions, respectively). Four hundred milliseconds after the appearance of the bigram-ordering, an underlined target bigram xo or ox replaced either the bigram marking the low probability transition (e.g., mn nm xo mn mn nm) or the bigram marking the high probability transition (e.g., mn nm nm xo mn nm). Thus processing of a potential target bigram during the 400 ms interval was not possible in this condition. Also, during the 400 ms interval, the identity of the marker (mn or nm) at any given location was not predictive of the upcoming target bigram (xo or ox).

The conditions in which the location markers were xo-ox and mn-nm were referred to as the Present and Absent conditions, respectively, because the target bigram was present/absent prior to the appearance of the underline. The Present and Absent conditions were identical except for the bigrams marking the target locations. It is reasonable, therefore, to assume that learning of the transition probabilities would be equivalent in the two conditions. Thus, a larger reaction time difference between low and high probability transitions in the Present than Absent condition would have to be attributed to the former's greater sensitivity to learning due to processing, during the 400

ms interval before the underline, of the bigram marking the high probability transition.

The fourth and final goal of the current study was to determine the complexity of the information that can be learned perceptually. More specifically, pure perceptual-based learning of first- (Experiments 1-3) and second-order (Experiment 4) transition probabilities was examined (see footnote 1). First-order probability information is less complex than second-order probability information because in the former, only the preceding target location is needed to differentially predict the next target location whereas in the latter, the preceding two target locations are required. Remillard and Clark (2001) showed that in the case of correlated sequences of target locations and responses, learning of second-order probabilities was possible but impaired relative to learning of first-order probabilities. I wished to determine whether this was the case with pure perceptual-based learning.

EXPERIMENT 1

The SRT task consisted of six target locations, two targets, and two response keys. The left and right keys were pressed in response to the target bigrams xo and ox, respectively. The sequence of responses was unstructured in that first-order probabilities were 1/2. For example, if the left key was pressed on trial t - 1, then the probabilities of a left and right key response on trial t were each 1/2. In contrast, the sequence of target locations was structured with first-order probabilities of 1/3 and 2/3. For example, if location 1 was the target location on trial t - 1, then the probability of locations 3 and 4 being the target location on trial t might be 1/3 and 2/3, respectively. Thus shorter reaction times on high than low probability transitions would be evidence for pure perceptual-based learning of the first-order probabilities. The Present and Absent

conditions were as described earlier.

Reaction times on low and high probability transitions were calculated as a function of the preceding context to avoid confounding type of transition with type of run completed. There were four types of five-element runs defined by whether the first and fourth elements were equal (E) or unequal (U) and the second and fifth elements were equal (E) or unequal (U) (see Table 1). For example, 1-4-2-1-3 is an EU run because the first and fourth elements are equal (E) and the second and fifth elements are unequal (U).

Table 1
Types of Five-Element Runs

Run	Example
EE	1-3-2-1-3
UE	6-3-2-1-3
EU	1-4-2-1-3
UU	6-4-2-1-3

Note. Five-element runs were categorized as a function of the first and fourth elements being equal (E) or unequal (U) and the second and fifth elements being equal (E) or unequal (U).

Remillard and Clark (2001) showed that reaction time to the last element was shorter for EE than UE runs and longer for EU than UU runs. For EE runs, the repetition of a bigram is correctly primed (e.g., 1-3-2-1 primes 3 and 3 occurs) producing a short reaction time. For EU runs, the repetition of a bigram is incorrectly primed (e.g., 1-4-2-1 primes 4 but 3 occurs) producing a long reaction time. Because a greater proportion of high than low probability transitions in the current study completed the faster EE and UU runs, type of run completed was a confound. However, by calculating reaction time as a function of run and averaging across runs, reaction times on low and high probability transitions are

equally affected by the different runs. Finally, if the priming mechanism affords processing of information at a primed target location before the cue (i.e., underline) is presented, then reaction time differences between runs should be greater in the Present than Absent condition.

Method

Participants

The participants were 24 university undergraduates ranging in age from 18 to 22 years.

SRT Task

The SRT task was run on a personal computer with standard monitor and keyboard. Millisecond timing was implemented using Bovens and Brysbaert's (1990) routine. There were six target locations marked with the bigrams xo and ox in the Present condition, and mn and nm in the Absent condition. The bigrams were arranged horizontally with adjacent bigrams separated by 2.1 cm. Each bigram was 0.6 cm in width and 0.4 cm in height. Viewing distance was approximately 55 cm. The 'V' and 'M' response keys, on which were placed the left and right index fingers, corresponded to the targets xo and ox, respectively. The response keys were marked with red stickers.

There were three sessions, one on each of three consecutive days. Sessions 1, 2, and 3 were each comprised of 16 blocks of trials with 110 trials per block. The nature of a trial is described in the Experimental Conditions section later. Session 1 began with a practice block of 99 trials.

A performance history was provided at the end of each block. The numbers 1 to 16, corresponding to the number of blocks in a session, appeared vertically along the side

of the screen. Beside the number for a completed block, one of two types of information was displayed. If 6% or more of the responses in the block were incorrect, the message "too many errors" and the error rate were displayed. Otherwise, a horizontal line, its length representing the average reaction time of correct responses, and the average reaction time were displayed. After a 10-second break, participants initiated the next block of trials at their discretion by pressing a key in response to a prompt on the screen.

Structure of the Sequences of Target Locations

Letting the numbers 1 to 6 represent the six target locations from left to right respectively, Table 2 presents the third-order probabilities and frequencies that were inherent in the sequences of target locations across every two blocks of trials. For example, row 1 indicates that the sequence 3-2-1 was followed by 3, four times and by 4, eight times; that is, $P(3|3-2-1) = 1/3$ and $P(4|3-2-1) = 2/3$ (labelled L and H for low and high probability transitions, respectively). Similarly, row 9 indicates that the sequence 1-3-2 was followed by 1, four times and by 6, four times; that is, $P(1|1-3-2) = 1/2$ and $P(6|1-3-2) = 1/2$ (labelled M for medium probability transitions). Set 2 transitions (L2, H2) immediately followed Set 1 transitions (L1, H1) in the sequences of target locations. For example, in the sequence 3-2-1-3-2, 3-2-1-3 is an L1 transition and it is immediately followed by the H2 transition 2-1-3-2.

Of interest were the first-order probabilities. First-order probabilities were 1/3, 1/2, and 2/3. For example, in Table 2, rows 1-4 indicate that 1 was followed by 3, twelve times and by 4, twenty-four times; that is $P(3|1) = 1/3$ and $P(4|1) = 2/3$. Similarly, rows 9-12 indicate that 2 was followed by 1, eighteen times and by 6, eighteen times; that is $P(1|2) = 1/2$ and $P(6|2) = 1/2$.

Table 2

Third-Order Probabilities (L = 1/3, M = 1/2, H = 2/3) and Frequencies (in parentheses) Inherent in the Sequences of Target Locations Across Every Two Blocks of Trials (Experiments 1-3)

Previous Target Locations	Next Target Location					
	1	2	3	4	5	6
3-2-1	--	--	L1 (4)	H1 (8)	--	--
4-2-1	--	--	L1 (2)	H1 (4)	--	--
3-5-1	--	--	L1 (2)	H1 (4)	--	--
4-5-1	--	--	L1 (4)	H1 (8)	--	--
3-2-6	--	--	H1 (8)	L1 (4)	--	--
4-2-6	--	--	H1 (4)	L1 (2)	--	--
3-5-6	--	--	H1 (4)	L1 (2)	--	--
4-5-6	--	--	H1 (8)	L1 (4)	--	--
1-3-2	M (4)	--	--	--	--	M (4)
6-3-2	M (8)	--	--	--	--	M (8)
1-4-2	M (4)	--	--	--	--	M (4)
6-4-2	M (2)	--	--	--	--	M (2)
1-3-5	M (2)	--	--	--	--	M (2)
6-3-5	M (4)	--	--	--	--	M (4)
1-4-5	M (8)	--	--	--	--	M (8)
6-4-5	M (4)	--	--	--	--	M (4)
2-1-3	--	H2 (4)	--	--	L2 (2)	--
5-1-3	--	H2 (4)	--	--	L2 (2)	--
2-6-3	--	H2 (8)	--	--	L2 (4)	--
5-6-3	--	H2 (8)	--	--	L2 (4)	--
2-1-4	--	L2 (4)	--	--	H2 (8)	--
5-1-4	--	L2 (4)	--	--	H2 (8)	--
2-6-4	--	L2 (2)	--	--	H2 (4)	--
5-6-4	--	L2 (2)	--	--	H2 (4)	--

Note. Dashes indicate that transitions did not occur. L1 = low probability transition from Set 1; H1 = high probability transition from Set 1; L2 = low probability transition from Set 2; H2 = high probability transition from Set 2.

The sequential structure was controlled so that certain types of information were not confounded with first-order probability. Each location was a target location equally often (i.e., P(1) = P(2) = ... = P(6) = 1/6), lag 3 probabilities[2] were 0.50 (e.g., P(4|3-x-x) = 0.50), and lag 2 probabilities and probabilities of the form $P(E|A_2-A_1-x)$ were 0.44, 0.50, or 0.56 (e.g., P(3|2-x) = 0.50 and P(5|2-1-x) = 0.56). Thus shorter reaction times on H

than L transitions would be evidence for learning of the first-order probabilities, although

learning of second- or third-order probabilities cannot be ruled out as these were

completely confounded with first-order probability (e.g., $P(3|1) = P(3|2\text{-}1) = P(3|3\text{-}2\text{-}1) =$

$1/3$). The confound is addressed in Experiment 4.

For each participant and each successive pair of blocks of trials, the sequence of

target locations was generated by submitting the frequencies in Table 2 to a sequence-

generation algorithm (Remillard & Clark, 1999). The algorithm randomly generated a

219-element sequence with the specified frequencies. Elements 1-110 and 110-219 each

comprised a block of 110 trials. For the practice block of 99 trials at the beginning of

session 1, the frequencies in Table 2 were replaced with the number 2. Thus the sequence

of target locations in the practice block was unstructured in that first-, second-, and third-

order probabilities were $1/2$.

To counterbalance sequences (e.g., 3-2-1-3) across L, H, and M transitions, six

versions of Table 2 were created. The six versions appear in Appendix A.

Types of runs. The 96 five-element runs were each classified into one of four

types on the basis of the first and fourth elements being equal (E) or unequal (U) and the

second and fifth elements being equal (E) or unequal (U) (see Table 1). If priming effects

are present, there should be a First (E, U) x Last (E, U) interaction with reaction time to

the last element being shorter for EE than UE runs and longer for EU than UU runs.

Structure of the Sequences of Targets and Responses

The sequences of targets, and hence left and right key responses, were

unstructured and independent of the sequences of target locations. For each participant

and each successive pair of blocks of trials, the sequence of targets was generated by

submitting the frequencies in Table 3 to a sequence-generation algorithm (Remillard &

Clark, 1999). The algorithm randomly generated a 227-element sequence with the

specified frequencies. For example, the sequence 1-1-1 was followed by 1, fourteen times

and by 2, fourteen times. Elements 1-110 and 111-220 each comprised a block of 110

trials. Because elements 221-227 were excluded, the frequencies in Table 3 were not

exact across the two blocks of trials. Thus, across every two blocks of trials, first-,

second-, and third-order probabilities in the sequences of targets and responses were

approximately 1/2. For the practice block of 99 trials at the beginning of session 1, the

frequencies in Table 3 were replaced with the number 6.

Table 3
Frequencies for the Sequences
of Targets (1 = xo, 2 = ox)
Across Every Two Blocks of
Trials (Experiments 1-4)

Previous Targets	Next Target	
	1	2
1-1-1	14	14
1-1-2	14	14
1-2-1	14	14
1-2-2	14	14
2-1-1	14	14
2-1-2	14	14
2-2-1	14	14
2-2-2	14	14

Note. Targets xo and ox
required left and right key
responses, respectively.

Experimental Conditions

There were two between-participant conditions. In the Present condition, location

markers were the bigrams xo and ox. On trial t, a double-dash (--) appeared below a

bigram marking one of the locations. Participants pressed the key corresponding to the

underlined target bigram. Immediately after a correct response, the line was erased and the location markers were changed as follows: If the target location on trial t + 1 was location A (where A represents one of the six target locations) and xo (ox) was the target on trial t + 1, then bigram xo (ox) marked location A. Bigrams to mark the remaining locations were chosen randomly with the constraint that locations 1 versus 6, 2 versus 5, and 3 versus 4 were marked with different bigrams. This ensured that L versus H transitions were marked with different bigrams (see Table 2). After a delay of 400 ms, trial t + 1 began with the line appearing below the bigram marking location A.

In the Absent condition, location markers were the bigrams mn and nm. On trial t, a target xo or ox replaced a bigram mn or nm marking one of the locations and a double-dash (--) appeared below the target. Participants pressed the key corresponding to the underlined target bigram. Immediately after a correct response, the target and line were erased and the location markers were changed at random with the constraint that locations 1 versus 6, 2 versus 5, and 3 versus 4 were marked with different bigrams. After a delay of 400 ms, trial t + 1 began.

The Present and Absent conditions were identical except for the bigrams marking the target locations. It is reasonable, therefore, to assume that learning of the first-order probabilities would be equivalent in the two conditions. Thus, a larger reaction time difference between L and H transitions in the Present than Absent condition would have to be attributed to the former's greater sensitivity to learning due to processing, during the 400 ms interval, of the bigram marking the high probability transition and preparation of the corresponding response. Such preparation should produce reaction time benefits if the line appears below the bigram marking the high probability transition and costs if it

appears below the different bigram marking the low probability transition.

Priming effects. Assuming that priming effects associated with the different types of runs were equivalent in the Present and Absent conditions, a larger reaction time difference between UE and EE runs and between EU and UU runs in the Present than Absent condition would have to be attributed to the Present condition's greater sensitivity to priming effects due to processing, during the 400 ms interval, of the bigram marking the primed target location (in the case of EE and EU runs) and preparation of the corresponding response. Such preparation should produce reaction time benefits if the line appears below the bigram marking the primed target location (EE runs) and costs if it appears below the different bigram marking the unprimed target location (EU runs).

Awareness Questionnaire

The questionnaire to assess awareness of the first-order probabilities consisted of six items with two options per item (see Appendix B). For each item, numbers represented target locations and participants had to choose the high-probability transition. For example, item 1 required participants to indicate, by circling one of the two numbers 3 or 4, whether the double-dash (--), after appearing in location 1, was more likely to appear in location 3 or location 4 next. Four items pertained to L/H transitions and two to M transitions. For example, with respect to Table 2, items 1, 2, 5, and 6 corresponded to L/H transitions, and items 3 and 4 to M transitions. Scores greater than 50% correct (random guessing performance) on the four items pertaining to L/H transitions would indicate awareness of the first-order probabilities. For reference while completing the questionnaire, the six target locations on the monitor were marked with the bigrams xx and nn for participants in the Present and Absent conditions, respectively.

Procedure

Twelve participants were randomly assigned to the Present condition and twelve to the Absent condition. Within each condition, two participants were randomly assigned to each version of Table 2 (see Appendix A). At the beginning of session 1, the SRT task was described and participants were instructed to try to improve their reaction time with practice while keeping their error rate below 6%. The structure underlying the sequence of target locations was never mentioned. Immediately following the last block of session 3, the awareness questionnaire was administered.

Results and Discussion

For each participant, the median reaction time of correct responses was determined as a function of transition (L, H), set (1, 2), run completed (EE, UE, EU, UU), and session (1, 2, 3). Figure 1 shows reaction time, averaged across set and run, as a function of transition, session, and condition (Present, Absent). Table 4 shows reaction time, averaged across transition and set, as a function of run, session, and condition.

Analyses of variance (ANOVAs) with transition (L, H), set (1, 2), first (E, U), last (E, U), and session (1, 2, 3) as within-participants factors were performed on the reaction time data from the Present and Absent conditions. When comparing the two conditions, presence (Present, Absent) was introduced as a between-participants factor. The session factor was broken down into its linear (Session-L) and quadratic (Session-Q) components to examine how differences in reaction time between transitions and between runs changed across sessions. None of the effects involving Session-Q approached significance and so only effects involving Session-L are reported. Tests for the effect of transition and the Transition x Presence interaction were one-tailed. I expected reaction

times to be shorter on H than L transitions and the difference to be greater in the Present

than Absent condition. Tests for all other effects were two-tailed. Alpha was .05.
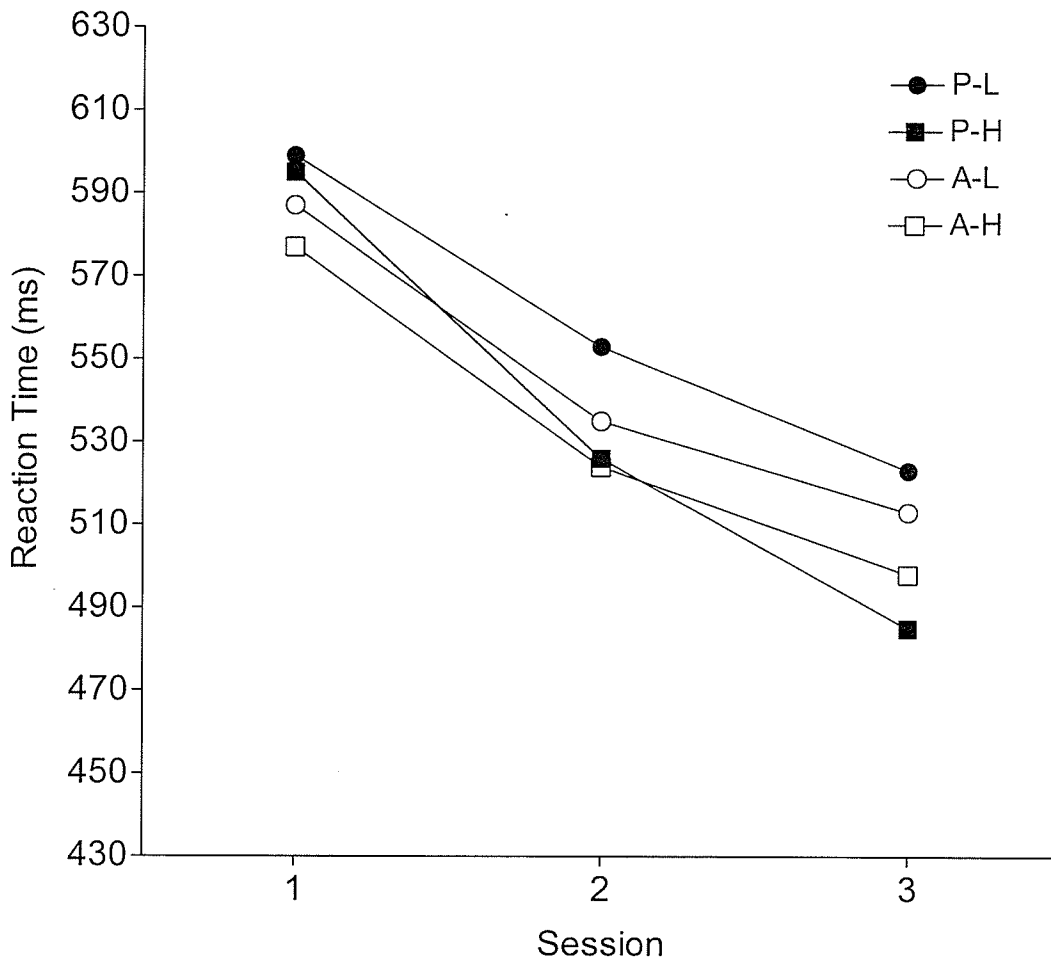
Figure 1. Reaction time, averaged across set (1, 2) and run (EE, UE, EU, UU), as a
function of transition (L, H), session (1, 2, 3), and condition (Present, Absent) in
Experiment 1. P = Present condition; A = Absent condition; L = low probability
transition; H = high probability transition.

Table 4
Reaction Time (ms), Averaged Across Transition (L, H) and Set (1, 2), as a Function of Run (EE, UE, EU, UU), Session (1, 2, 3), Condition (Present, Absent), and Experiment (1-3)

		Present				Absent			
		Session				Session			
Exp.	Run	1	2	3	Mean	1	2	3	Mean
1	EE	599	538	503	547	581	533	506	540
	UE	596	547	515	553	581	529	509	540
	EU	602	538	503	548	581	531	506	539
	UU	591	535	493	540	583	525	501	536
2					Consistent group				
	EE	603	557	539	566	536	500	492	509
	UE	615	566	547	576	543	504	492	513
	EU	614	563	540	572	546	497	491	511
	UU	607	556	538	567	543	498	491	511
					Inconsistent group				
	EE	611	563	531	568	549	510	494	518
	UE	617	568	548	578	549	512	493	518
	EU	610	557	529	565	546	509	494	516
	UU	610	553	522	562	553	505	494	517
3					Difficult group				
	EE	627	567	533	576	606	546	531	561
	UE	636	569	552	586	614	552	528	565
	EU	628	565	539	577	612	546	525	561
	UU	628	561	523	571	613	548	520	560
					No-Mask group				
	EE	620	566	542	576	503	467	451	474
	UE	624	572	547	581	506	468	448	474
	EU	620	563	535	573	503	465	447	472
	UU	620	558	521	566	502	469	445	472

Note. Exp. = Experiment

Present Condition

The effect of transition was significant, $F(1, 11) = 5.86$, $MSE = 13,275.09$, $p = .017$, as was the Transition x Session-L interaction, $F(1, 11) = 16.24$, $MSE = 1,629.83$, $p = .002$. Thus reaction time was shorter on H than L transitions and the difference increased across sessions. This clearly indicates learning of the first-order probabilities.

The First x Last interaction was significant, $F(1, 11) = 14.41$, $MSE = 478.70$, $p = .003$, reflecting the shorter reaction times on EE than UE runs and longer reaction times

on EU than UU runs. Thus priming effects were present.[3] The First x Last x Session-L interaction was not significant, $F(1, 11) = 2.53$, $MSE = 439.70$, $p = .140$. The preceding interactions did not interact significantly with transition, two $ps > .164$, indicating that priming effects did not vary significantly as a function of transition.

Absent Condition

The effect of transition was significant, $F(1, 11) = 3.55$, $MSE = 6,138.25$, $p = .043$, whereas the Transition x Session-L interaction was not, $F(1, 11) = 1.44$, $MSE = 539.77$, $p = .256$. Thus reaction time was shorter on H than L transitions, indicating learning of the first-order probabilities.

The First x Last interaction, $F(1, 11) = 2.47$, $MSE = 104.28$, $p = .145$, and First x Last x Session-L interaction, $F(1, 11) = 2.68$, $MSE = 235.23$, $p = .130$, were not significant. Thus there was no evidence for priming effects. The preceding interactions did not interact significantly with transition, two $ps > .634$.

Present Versus Absent Condition

The Transition x Presence interaction was not significant, $F(1, 22) = .89$, $MSE = 9,706.67$, $p = .174$. However, the Transition x Presence x Session-L interaction was significant, $F(1, 22) = 8.38$, $MSE = 1,084.80$, $p = .008$. Thus the reaction time difference between L and H transitions increased at a faster rate across sessions in the Present than Absent condition. In session 3, the Transition x Presence interaction was not significant, $F(1, 22) = 2.38$, $MSE = 5,061.60$, $p = .069$.

The nonsignificant Transition x Presence interactions were due to the variability in the reaction time difference between L and H transitions across the six versions of Table 2. To remove this variability from the error terms, version (1-6) was introduced as

a between-participants factor and the analysis rerun. The Transition x Presence interaction now approached significance, $F(1, 12) = 3.13$, $MSE = 2,746.65$, $p = .051$, and the Transition x Presence x Session-L interaction was still significant, $F(1, 12) = 8.94$, $MSE = 1,016.76$, $p = .011$. In session 3, the Transition x Presence interaction was now significant, $F(1, 12) = 9.04$, $MSE = 1,334.04$, $p = .006$. Thus the reaction time difference between L and H transitions was greater in the Present than Absent condition. Finally, the preceding interactions did not interact significantly with version, three $ps > .293$.

In sum, the reaction time difference between L and H transitions increased at a faster rate across sessions in the Present than Absent condition and the difference was greater in the former than latter condition. Assuming that learning of the first-order probabilities was equivalent in the two conditions, the results suggest that in the Present condition, participants processed, during the 400 ms interval, the bigram marking the high probability transition and prepared the corresponding response.

Turning to the runs, the First x Last x Presence interaction was significant, $F(1, 22) = 7.70$, $MSE = 291.49$, $p = .011$, reflecting the greater reaction time difference between UE and EE runs and between EU and UU runs in the Present than Absent condition. Assuming that priming effects were equivalent in the two conditions, the result suggests that in the Present condition, participants processed, during the 400 ms interval, the bigram marking the primed target location (in the case of EE and EU runs) and prepared the corresponding response. The First x Last x Presence x Session-L interaction was not significant, $F(1, 22) = .10$, $MSE = 337.46$, $p = .753$.

Finally, overall reaction times (i.e., reaction time averaged across L and H transitions) were similar in the Present and Absent conditions. The effect of presence was

not significant, $F(1, 22) = .17$, $MSE = 106,377.06$, $p = .684$, nor was the Presence x

Session-L interaction, $F(1, 22) = 1.49$, $MSE = 9,473.50$, $p = .236$. This rules out the

possibility that the larger reaction time differences between L and H transitions and

between runs in the Present than Absent condition were an artifact of overall reaction

time differences between conditions (e.g., see Chapman, Chapman, Curran, & Miller,

1994; Curran, 1997, p. 27) or the result of differences in difficulty (e.g., greater learning

of the first-order probabilities or greater priming effects in the Present than Absent

condition because the former was more or less difficult than the latter).

Awareness of First-Order Probabilities

On the awareness questionnaire, the percentage of the four items pertaining to

L/H transitions receiving correct responses (i.e., for which H transitions were chosen) was

determined for each participant. In the Present condition, the mean percent correct was

56.25% which did not differ significantly from what would be expected by random

guessing on the questionnaire (50% correct), $F(1, 11) = .37$, $MSE = 1,264.20$, $p = .555$.

Twenty-seven and 21 of the 48 items (4 items x 12 participants) received correct and

incorrect responses, respectively. These frequencies did not differ significantly from what

would be expected by random guessing on the questionnaire (24 and 24, respectively),

$X^2(1) = .75$, $p = .386$. Thus there was no evidence in the Present condition for awareness

of the first-order probabilities.

In the Absent condition, the mean percent correct was 56.25% which did not

differ significantly from what would be expected by random guessing on the

questionnaire (50% correct), $F(1, 11) = .80$, $MSE = 582.39$, $p = .389$. Twenty-seven and

21 of the 48 items (4 items x 12 participants) received correct and incorrect responses,

respectively. These frequencies did not differ significantly from what would be expected

by random guessing on the questionnaire (24 and 24, respectively), $X^2(1) = .75, p = .386$.

Thus there was no evidence in the Absent condition for awareness of the first-order

probabilities.[4]

<div align="center">EXPERIMENT 2</div>

Results from the Present condition in Experiment 1 and in the experiment outlined

in Footnote 4 clearly show that pure perceptual-based learning of first-order probabilities

is possible when target locations are horizontally arranged and separated by relatively

narrow distances. Moreover, the Present-Absent differences in performance in

Experiment 1 suggest that the mechanism underlying pure perceptual-based learning

affords processing of information at an anticipated target location before the cue (i.e.,

underline) is presented.

Alternatively, the Present-Absent differences in performance could have been due

to greater learning of the first-order probabilities in the Present than Absent condition

rather than to processing bigrams marking anticipated target locations in the Present

condition. Although this is unlikely, given that the two conditions were identical except

for the bigrams marking the target locations and were equally difficult as indicated by

similar overall reaction times, it cannot be ruled out. In Experiment 2, a within-

participants design was used. Participants alternated between the Present and Absent

conditions. Under those circumstances, I assumed that knowledge of the first-order

probabilities in the Present condition would fully transfer to the Absent condition. Thus a

replication of the Present-Absent differences in Experiment 1 could not then be attributed

to differences in knowledge of the first-order probabilities.

The assumption of complete transfer of first-order probability knowledge from the Present condition to the Absent condition is a strong one and may be difficult to verify empirically. However, I tested for some transfer by comparing performance in two groups. In the Consistent group, L and H transitions in the Absent condition were the same as those in the Present condition. In the Inconsistent group, L and H transitions in the Absent condition were the reverse of those in the Present condition. For example, if 1-3 and 1-4 were, respectively, L and H transitions in the Present condition, then in the Absent condition they were L and H transitions in the Consistent group and H and L transitions in the Inconsistent group. If there is little or no transfer of first-order probability knowledge from the Present condition to the Absent condition, then reaction time differences between L and H transitions in the Absent condition should be similar in the Consistent and Inconsistent groups. Conversely, if there is some transfer of knowledge, then reaction time differences between L and H transitions in the Absent condition should be smaller in the Inconsistent group than in the Consistent group.

The second purpose of Experiment 2 was to use a shorter distance between adjacent target locations than in Experiment 1. The distance was reduced from 2.1 cm to 1.1 cm.

Method

Participants

The participants were 24 university undergraduates ranging in age from 17 to 34 years.

SRT Task

The SRT task was identical to that in Experiment 1 except that adjacent target

locations were separated by 1.1 cm and in each session, training alternated between two blocks in the Present condition and two blocks in the Absent condition. There were two orders. In the first order, blocks 1-2, 5-6, 9-10, and 13-14 were the Present condition and blocks 3-4, 7-8, 11-12, and 15-16 were the Absent condition. In the second order, the assignments were reversed. Session 1 began with a practice block of 99 trials performed under the Present condition.

Structure of the Sequences of Target Locations

The sequences of target locations were structured and generated as in Experiment 1. In the Consistent group, L and H transitions in the Absent condition were the same as those in the Present condition. In the Inconsistent group, L and H transitions in the Absent condition were the reverse of those in the Present condition. Specifically, if the structure of the sequences of target locations in the Present condition was version 1, 2, 3, 4, 5, or 6 of Table 2 (see Appendix A), then the structure in the Absent condition was, respectively, versions 1, 2, 3, 4, 5, and 6 in the Consistent group and versions 2, 1, 4, 3, 6, and 5 in the Inconsistent group.

Structure of the Sequences of Targets and Responses

The sequences of targets, and hence left and right key responses, were generated as in Experiment 1.

Experimental Conditions

The Present and Absent conditions were as in Experiment 1 except that they were within- rather than between-participants.

Awareness Questionnaire

The awareness questionnaire was identical to that in Experiment 1. For each item,

participants were instructed to choose the high-probability transition. There was no mention of whether they should refer to the Present or Absent condition. For reference while participants completed the questionnaire, the six target locations were marked with the bigram xx.

Procedure

The Consistent and Inconsistent groups were each run in a separate experiment with 12 participants per group. Within each group, one participant was randomly assigned to each of the 12 cells created by crossing order of Present-Absent blocks (first, second) and version of Table 2 for the Present condition (1-6). At the beginning of session 1, the SRT task was described and participants were instructed to try to improve their reaction time with practice while keeping their error rate below 6%. The structure underlying the sequence of target locations was never mentioned. Immediately following the last block of session 3, the awareness questionnaire was administered.

Results and Discussion

For each participant, the median reaction time of correct responses was determined as a function of transition (L, H), set (1, 2), run completed (EE, UE, EU, UU), session (1, 2, 3), and condition (Present, Absent). Figure 2 shows reaction time, averaged across set and run, as a function of transition, session, condition, and group (Consistent, Inconsistent). Table 4 shows reaction time, averaged across transition and set, as a function of run, session, condition, and group.

ANOVAs were as in Experiment 1 except that presence (Present, Absent) was a within-participants factor. When comparing the Consistent and Inconsistent groups, consistency (Consistent, Inconsistent) and version (1-6) were introduced as between-

participants factors.
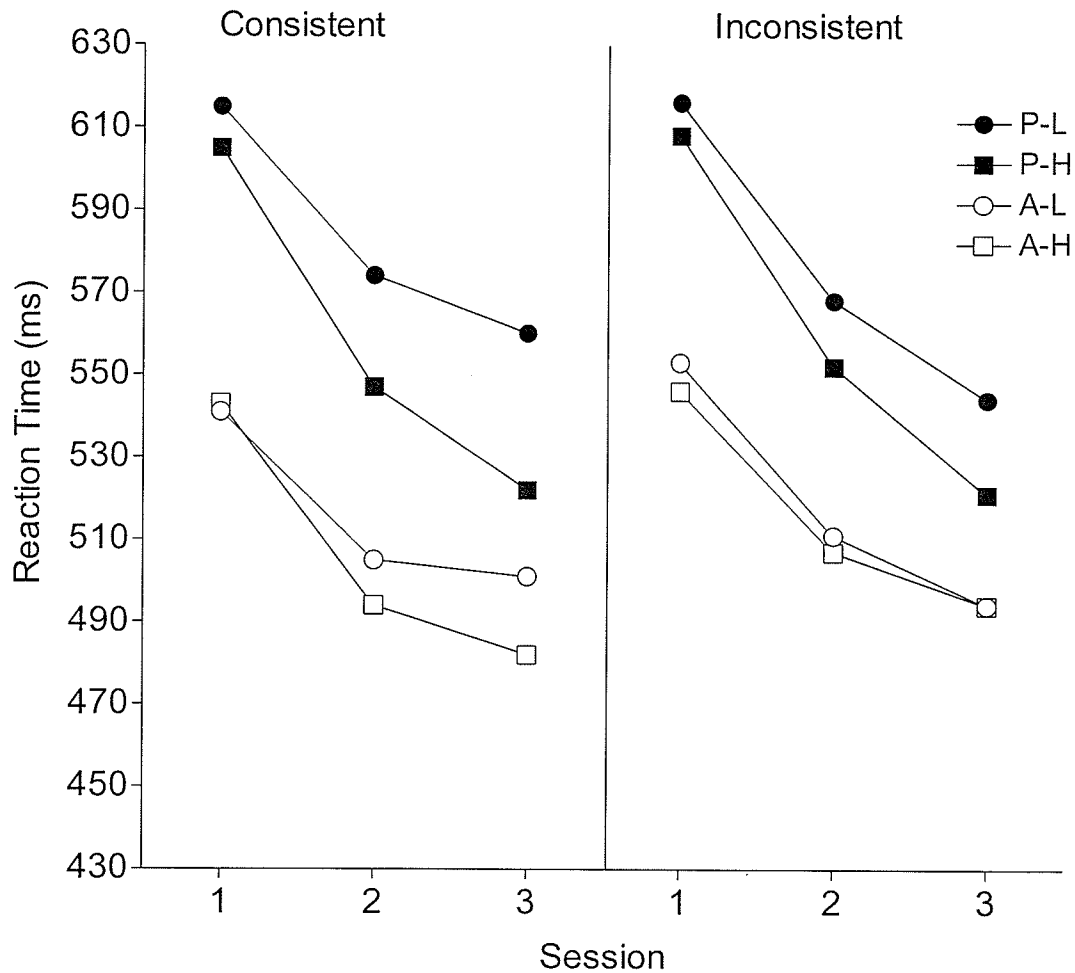
Figure 2. Reaction time, averaged across set (1, 2) and run (EE, UE, EU, UU), as a function of transition (L, H), session (1, 2, 3), condition (Present, Absent), and group (Consistent, Inconsistent) in Experiment 2. P = Present condition; A = Absent condition; L = low probability transition; H = high probability transition.

Present Condition

Consistent group. The effect of transition was significant, $F(1, 11) = 7.72$, $MSE = 11,476.34$, $p = .009$, as was the Transition x Session-L interaction, $F(1, 11) = 10.47$, $MSE = 1,757.16$, $p = .008$. Thus reaction time was shorter on H than L transitions and the difference increased across sessions. This indicates learning of the first-order probabilities.

The First x Last interaction was significant, $F(1, 11) = 6.35$, $MSE = 1,228.43$, $p = .028$, reflecting the shorter reaction times on EE than UE runs and longer reaction times on EU than UU runs. Thus priming effects were present. The First x Last x Session-L interaction was not significant, $F(1, 11) = 1.26$, $MSE = 378.18$, $p = .285$. The preceding interactions did not interact significantly with transition, two $ps > .333$.

Inconsistent group. The effect of transition was significant, $F(1, 11) = 5.03$, $MSE = 7,076.85$, $p = .023$, whereas the Transition x Session-L interaction was not, $F(1, 11) = 1.72$, $MSE = 3,137.72$, $p = .217$. Thus reaction time was shorter on H than L transitions and the difference did not increase significantly across sessions.

The First x Last interaction was significant, $F(1, 11) = 5.81$, $MSE = 1,086.38$, $p = .035$, reflecting the shorter reaction times on EE than UE runs and longer reaction times on EU than UU runs. Thus priming effects were present. The First x Last x Session-L interaction was also significant, $F(1, 11) = 5.51$, $MSE = 335.64$, $p = .039$, reflecting the increase in reaction time differences between runs across sessions. The preceding interactions did not interact significantly with transition, two $ps > .773$.

Consistent versus inconsistent group. The Transition x Consistency interaction, $F(1, 12) = 2.08$, $MSE = 2,850.26$, $p = .175$, and Transition x Consistency x Session-L

interaction, $F(1, 12) = 1.19$, $MSE = 1,623.81$, $p = .296$, were not significant. Although reaction time differences between L and H transitions did not differ significantly across the two groups, there is some evidence that performance in the Inconsistent group was impaired by the reversal of L and H transitions across the Present and Absent conditions. The reaction time difference between L and H transitions did not increase significantly across sessions in the Inconsistent group, but did do so in the Consistent group as well as in Experiment 1, in the experiment outlined in footnote 4, and in two other "Consistent" groups in the next experiment.[5]

Absent Condition

    Consistent group. The effect of transition was not significant, $F(1, 11) = 2.37$, $MSE = 5,155.73$, $p = .076$. However, the Transition x Session-L interaction was significant, $F(1, 11) = 15.55$, $MSE = 641.47$, $p = .002$. Thus the reaction time difference between L and H transition increased across sessions. In session 3, reaction time was shorter on H than L transitions, $F(1, 11) = 5.19$, $MSE = 3,169.62$, $p = .022$.

    The First x Last interaction, $F(1, 11) = 2.51$, $MSE = 249.71$, $p = .141$, and First x Last x Session-L interaction, $F(1, 11) = 2.03$, $MSE = 296.78$, $p = .182$, were not significant. Thus there was no evidence for priming effects. The preceding interactions did not interact significantly with transition, two $ps > .553$.

    Inconsistent group. The effect of transition was not significant, $F(1, 11) = .46$, $MSE = 3,412.22$, $p = .257$, nor was the Transition x Session-L interaction, $F(1, 11) = 1.65$, $MSE = 845.56$, $p = .226$. Thus there was no evidence for shorter reaction times on H than L transitions.

    The First x Last interaction, $F(1, 11) = .18$, $MSE = 247.56$, $p = .684$, and First x

Last x Session-L interaction, $F(1, 11) = 2.63$, $MSE = 92.24$, $p = .133$, were not significant. Thus there was no evidence for priming effects. The preceding interactions did not interact significantly with transition, two $ps > .241$.

Consistent versus inconsistent group. The Transition x Consistency interaction was not significant, $F(1, 12) = 2.40$, $MSE = 1,049.68$, $p = .147$. However, the Transition x Consistency x Session-L interaction was significant, $F(1, 12) = 19.85$, $MSE = 473.93$, $p = .001$, reflecting the increasing reaction time difference between L and H transitions across sessions in the Consistent but not Inconsistent group. In session 3, the Transition x Consistency interaction was significant, $F(1, 12) = 20.02$, $MSE = 432.29$, $p = .001$. Thus the reaction time difference between L and H transitions was greater in the Consistent than Inconsistent group. The preceding results strongly suggest that there was transfer of first-order probability knowledge from the Present condition to the Absent condition. If there had been no transfer of knowledge, the pattern of reaction time differences between L and H transitions would have been similar in the Consistent and Inconsistent groups.

Present Versus Absent Condition (Consistent Group)

In the Consistent group, the Transition x Presence interaction was significant, $F(1, 11) = 9.13$, $MSE = 1,914.96$, $p = .006$, whereas the Transition x Presence x Session-L interaction was not, $F(1, 11) = 1.57$, $MSE = 408.04$, $p = .236$. Thus the reaction time difference between L and H transitions was greater in the Present than Absent condition.

Assuming that knowledge of the first-order probabilities transferred fully from the Present to the Absent condition, the preceding result cannot be attributed to greater first-order probability knowledge in the Present than Absent condition and therefore suggests that in the Present condition, participants processed, during the 400 ms interval, the

bigram marking the high probability transition and prepared the corresponding response. Although the assumption of complete transfer of first-order probability knowledge from the Present to the Absent condition may be difficult to test empirically, performance differences between the Consistent and Inconsistent groups in the Absent condition suggest there was some transfer.

Although the First x Last interaction was significant in the Present but not Absent condition, the First x Last x Presence interaction was not significant, $F(1, 11) = 2.90$, $MSE = 691.18$, $p = .117$. The First x Last x Presence x Session-L interaction was also not significant, $F(1, 11) = .02$, $MSE = 177.02$, $p = .888$. To increase power, the data from the Consistent and Inconsistent groups were combined. The First x Last x Presence interaction was now significant, $F(1, 12) = 8.81$, $MSE = 632.75$, $p = .012$, reflecting the greater reaction time difference between UE and EE runs and between EU and UU runs in the Present than Absent condition. Assuming that priming effects were equivalent in the two conditions, the result suggests that in the Present condition, participants processed, during the 400 ms interval, the bigram marking the primed target location (in the case of EE and EU runs) and prepared the corresponding response. The First x Last x Presence x Session-L interaction was not significant, $F(1, 12) = 1.10$, $MSE = 206.20$, $p = .314$. The two preceding interactions did not interact significantly with consistency, two $ps > .405$, suggesting that it was legitimate to combine the data from the Consistent and Inconsistent groups in order to increase power.

Finally, in the Consistent group, the effect of presence was significant, $F(1, 11) = 62.08$, $MSE = 16,231.41$, $p < .001$, as was the Presence x Session-L interaction, $F(1, 11) = 5.61$, $MSE = 2,996.60$, $p = .037$. Thus, unlike in Experiment 1, overall reaction time

was longer in the Present than Absent condition and the difference diminished across sessions. The more narrowly separated target locations in Experiment 2 than in Experiment 1 may have allowed for quicker target detection and orientation in the Absent condition or slower target identification in the Present condition due to increased interference from target-incompatible bigrams marking the locations (e.g., see Cohen & Shoup, 1997; Gathercole & Broadbent, 1987; Miller, 1991).

The effect of presence in the Consistent group raises the possibility that the larger reaction time differences between L and H transitions and between runs in the Present than Absent condition were not the result of processing bigrams marking anticipated target locations in the Present condition but rather, were an artifact of overall reaction time differences between conditions (e.g., see Chapman et al., 1994) or the result of differences in difficulty (e.g., greater use of first-order probability knowledge or greater priming effects in the Present than Absent condition because the former was more difficult than the latter). However, the next experiment shows that overall reaction time differences (and hence differences in difficulty) between the Present and Absent conditions cannot explain the larger reaction time differences between L and H transitions and between runs in the former than latter condition.

Awareness of First-Order Probabilities

On the awareness questionnaire, the percentage of the four items pertaining to L/H transitions receiving correct responses (i.e., for which H transitions were chosen) was determined for each participant.

Consistent group. The mean percent correct was 37.5% which did not differ significantly from what would be expected by random guessing on the questionnaire

(50% correct), $F(1, 11) = 3.67$, $MSE = 511.36$, $p = .082$. Eighteen and 30 of the 48 items (4 items x 12 participants) received correct and incorrect responses, respectively. These frequencies did not differ significantly from what would be expected by random guessing on the questionnaire (24 and 24, respectively), $X^2(1) = 3.00$, $p = .083$. Thus, there was no evidence for awareness of the first-order probabilities. Indeed, there was actually a tendency for choosing L transitions over H transitions on the questionnaire.

Inconsistent group. When the questionnaire was scored with respect to the Present condition, the mean percent correct was 50.0% which was exactly what would be expected by random guessing on the questionnaire. Twenty-four and 24 of the 48 items (4 items x 12 participants) received correct and incorrect responses, respectively. These frequencies were exactly what would be expected by random guessing on the questionnaire. The results were identical when the questionnaire was scored with respect to the Absent condition. Thus there was no evidence for awareness of the first-order probabilities.

EXPERIMENT 3

The purpose of Experiment 3 was to show that the larger reaction time differences between L and H transitions and between runs in the Present than Absent condition were not the result of overall reaction time differences (and hence differences in difficulty) between conditions, nor the result of forward masking of the targets xo and ox by the bigrams mn and nm in the Absent condition (e.g., see Scharf & Lefton, 1970; Schiller, 1966). Forward masking in the Absent condition may have slowed responding to the targets, especially at anticipated target locations where attention might have been focussed.

There were two groups in Experiment 3, both identical to the Consistent group in Experiment 2 except for the stimuli marking the target locations in the Absent condition. In the Difficult group, location markers in the Absent condition were the bigrams xx and oo. I assumed these bigrams, relative to the bigrams mn and nm, would increase the difficulty of responding to the targets xo and ox and better equate overall reaction times in the Present and Absent conditions. In the No-Mask group, location markers in the Absent condition were short lines above which a target appeared, thus eliminating the possibility of forward masking. If Present-Absent differences with respect to reaction time differences between L and H transitions and between runs do not vary across the Consistent, Difficult, and No-Mask groups but overall reaction time differences between the two conditions do vary across groups, then this would suggest that the larger reaction time differences between L and H transitions and between runs in the Present than Absent condition were not the result of overall reaction time differences (and hence differences in difficulty) between the two conditions nor the result of forward masking in the Absent condition but rather, the result of processing bigrams marking anticipated target locations in the Present condition.

Method

The participants were 24 university undergraduates ranging in age from 17 to 33 years. There were 12 participants in each of the Difficult and No-Mask groups. Each group was run in a separate experiment that was identical to the Consistent group in Experiment 2 except for the stimuli marking the target locations in the Absent condition. In the Difficult group, the bigrams mn and nm were replaced with the bigrams xx and oo, respectively. In the No-Mask group, the bigrams mn and nm were replaced with a double-

dash (--) and on each trial, a target appeared above one of the lines.

Results and Discussion

For each participant, the median reaction time of correct responses was determined as a function of transition (L, H), set (1, 2), run completed (EE, UE, EU, UU), session (1, 2, 3), and condition (Present, Absent). Figure 3 shows reaction time, averaged across set and run, as a function of transition, session, condition, and group (Difficult, No-Mask). Table 4 shows reaction time, averaged across transition and set, as a function of run, session, condition, and group.

ANOVAs were as in Experiment 1 except that presence (Present, Absent) was a within-participants factor. When comparing the Consistent (see Figure 2), Difficult, and No-Mask groups, difficulty (Consistent, Difficult, No-Mask) and version (1-6) were introduced as between-participants factors.

Present Condition

The effect of transition, the Transition x Session-L interaction, and the First x Last interaction were significant in both the Difficult and No-Mask groups, six $F(1, 11)$s > 5.20, six ps < .023. Moreover, none of the preceding three effects interacted significantly with difficulty, three $F(2, 18)$s < 1.37, three ps > .280. Thus reaction time differences between L and H transitions and between runs in the Present condition were similar across the Consistent, Difficult, and No-Mask groups. Finally, the effect of difficulty was not significant, $F(2, 18) = .07$, $MSE = 103,886.24$, $p = .932$, indicating that overall reaction times in the Present condition did not differ significantly across the three groups.

Absent Condition

The effect of transition was significant in the Difficult group, $F(1, 11) = 5.35$, $p =$
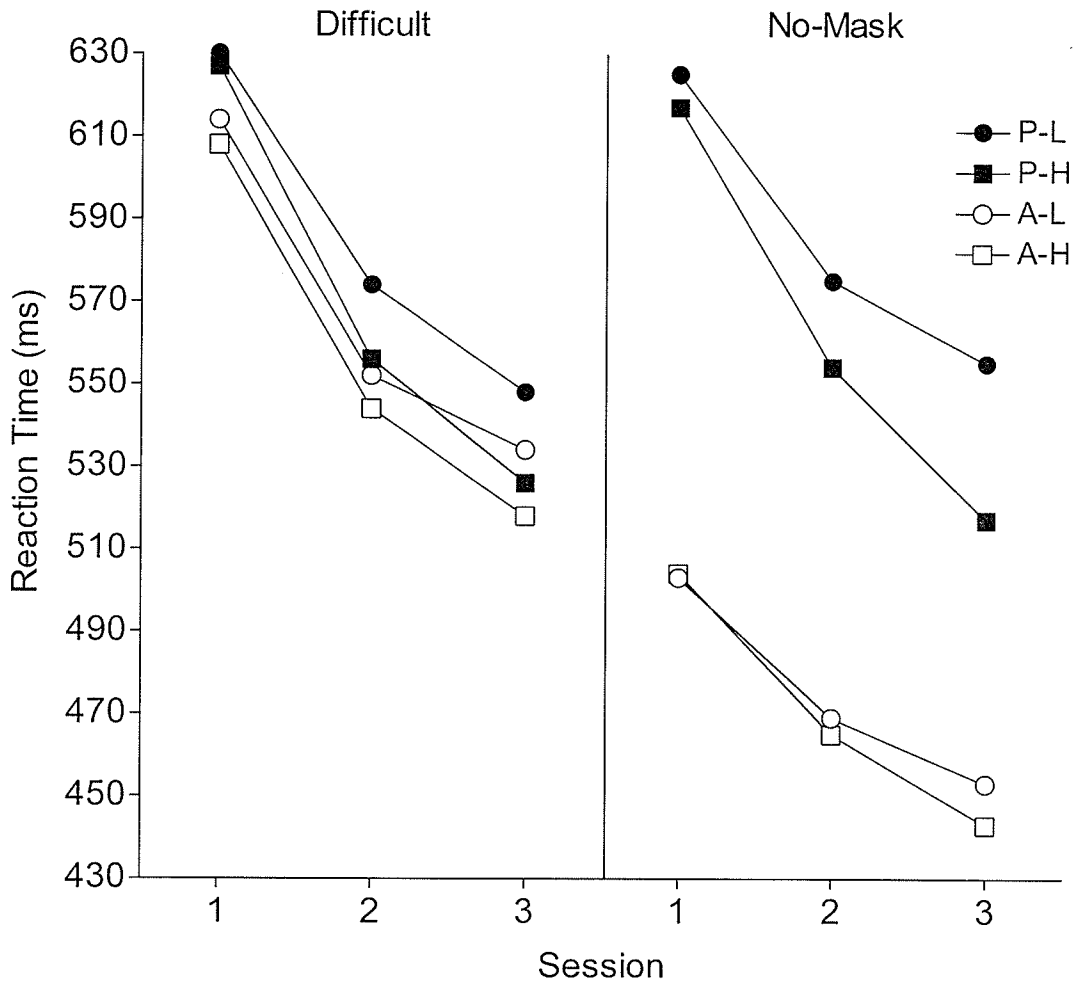
Figure 3. Reaction time, averaged across set (1, 2) and run (EE, UE, EU, UU), as a function of transition (L, H), session (1, 2, 3), condition (Present, Absent), and group (Difficult, No-Mask) in Experiment 3. P = Present condition; A = Absent condition; L = low probability transition; H = high probability transition.

.021, but not in the No-Mask group, $F(1, 11) = 1.01, p = .168$. However, the Transition x

Session-L interaction was significant in the No-Mask group, $F(1, 11) = 16.64, p = .002$,

and approached significance in the Difficult group, $F(1, 11) = 3.95, p = .072$. The First x

Last interaction was not significant in either group, two $F(1, 11)$s < 1.71, two $ps > .218$.

None of the preceding three effects interacted significantly with difficulty, three $F(2, 18)$s

< 1.92, three $ps > .176$. Thus reaction time differences between L and H transitions and

between runs in the Absent condition were generally similar across the Consistent,

Difficult, and No-Mask groups in spite of a significant effect of difficulty, $F(2, 18) =$

$11.87, MSE = 96,776.24, p = .001$, indicating that overall reaction times in the Absent

condition differed across the three groups. This suggests that the reaction time differences

between L and H transitions and between runs were not affected by overall reaction times

or by forward masking.

Present Versus Absent Condition

The Transition x Presence interaction and First x Last x Presence interaction were

significant in both the Difficult and No-Mask groups, four $F(1, 11)$s > 4.86, four $ps <$

.026. The Transition x Presence x Session-L interaction was significant in the No-Mask

group, $F(1, 11) = 7.80, p = .017$, but not in the Difficult group, $F(1, 11) = .63, p = .443$.

None of the preceding three effects interacted significantly with difficulty, three $F(2, 18)$s

< 1.77, three $ps > .199$. Thus Present-Absent differences with respect to reaction time

differences between L and H transitions and between runs were similar across the

Consistent, Difficult, and No-Mask groups in spite of a significant Presence x Difficulty

interaction, $F(2, 18) = 121.85, MSE = 4,332.11, p < .001$, indicating that the overall

reaction time difference between the Present and Absent conditions differed across the

three groups. This suggests that the larger reaction time differences between L and H

transitions and between runs in the Present than Absent condition were not the result of

overall reaction time differences (and hence differences in difficulty) between the two

conditions nor the result of forward masking in the Absent condition but rather, the result

of processing bigrams marking anticipated target locations in the Present condition.

Awareness of First-Order Probabilities

On the awareness questionnaire, the percentage of the four items pertaining to

L/H transitions receiving correct responses (i.e., for which H transitions were chosen) was

determined for each participant.

Difficult group. The mean percent correct was 54.2% which did not differ

significantly from what would be expected by random guessing on the questionnaire

(50% correct), $F(1, 11) = .21$, $MSE = 1,003.79$, $p = .658$. Twenty-six and 22 of the 48

items (4 items x 12 participants) received correct and incorrect responses, respectively.

These frequencies did not differ significantly from what would be expected by random

guessing on the questionnaire (24 and 24, respectively), $X^2(1) = .33$, $p = .564$. Thus there

was no evidence for awareness of the first-order probabilities.

No-Mask group. The mean percent correct was 83.3% which was greater than

what would be expected by random guessing on the questionnaire (50% correct), $F(1, 11)$

$= 35.20$, $MSE = 378.79$, $p < .001$. Forty and 8 of the 48 items (4 items x 12 participants)

received correct and incorrect responses, respectively. These frequencies differed from

what would be expected by random guessing on the questionnaire (24 and 24,

respectively), $X^2(1) = 21.33$, $p < .001$. It is not clear why there was awareness of the first-

order probabilities in the No-Mask group. Importantly, awareness did not seem to have an

effect on the reaction time differences between L and H transitions (also see Remillard &

Clark, 2001). The reaction time differences were similar to those in the Consistent and

Difficult groups where there was no evidence for awareness of the first-order

probabilities. Also, the reaction time differences in the Absent condition of the No-Mask

group were comparable to those in an early pilot study that was very similar to the Absent

condition and where there was no evidence for awareness of the first-order probabilities.

In the pilot study, the reaction time difference between L and H transitions increased

from 2 ms in session 1 to 16 ms in session 3.

EXPERIMENT 4

Experiments 1-3 examined pure perceptual-based learning of first-order

probabilities. However, second- and third-order probabilities were confounded with first-

order probability in those experiments (e.g., in Table 2, $P(3|1) = P(3|2\text{-}1) = P(3|3\text{-}2\text{-}1) =$

1/3). Thus the shorter reaction times on H than L transitions could have been due to

learning of second- or third-order probabilities rather than to learning of first-order

probabilities.

Experiment 4 sought to rule out this possibility and to examine pure perceptual-

based learning of second-order probabilities. Experiment 4 was identical to the Consistent

group in Experiment 2 except that in the sequence of target locations, first-order

probabilities no longer varied and were now 1/2. Second- and third-order probabilities

were still 1/3 and 2/3. Learning in Experiment 4 was therefore limited to second- or third-

order probabilities. Learning of first-order probabilities was not possible. Thus shorter

reaction times on H than L transitions would be evidence for learning of second-order

probabilities. Moreover, if the pattern of reaction time differences between L and H

transitions in Experiment 4 differed from that in the Consistent group of Experiment 2, this would indicate that learning in Experiment 2 was not limited to second- or third-order probabilities and therefore emcompassed first-order probabilities.

Method

The participants were 12 university undergraduates ranging in age from 17 to 27 years. All aspects of the current experiment were identical to those of the Consistent group in Experiment 2 except there were four sessions of training, first-order probabilities in the sequences of target locations were 1/2, and the awareness questionnaire assessed awareness of second-order probabilities.

Structure of the Sequences of Target Locations

Letting the numbers 1 to 6 represent the six target locations from left to right respectively, Table 5 presents the third-order probabilities and frequencies that were inherent in the sequences of target locations across every two blocks of trials. For example, row 1 indicates that the sequence 3-2-1 was followed by 3, three times and by 4, six times; that is, $P(3|3\text{-}2\text{-}1) = 1/3$ and $P(4|3\text{-}2\text{-}1) = 2/3$ (labelled L and H for low and high probability transitions, respectively). Similarly, row 9 indicates that the sequence 1-3-2 was followed by 1, six times and by 6, six times; that is, $P(1|1\text{-}3\text{-}2) = 1/2$ and $P(6|1\text{-}3\text{-}2) = 1/2$ (labelled M for medium probability transitions). Set 2 transitions (L2, H2) immediately followed Set 1 transitions (L1, H1) in the sequences of target locations.

Of interest were the second-order probabilities. Second-order probabilities were 1/3, 1/2, and 2/3. For example, in Table 5, rows 1 and 2 indicate that the sequence 2-1 was followed by 3, six times and by 4, twelve times; that is $P(3|2\text{-}1) = 1/3$ and $P(4|2\text{-}1) = 2/3$. Similarly, rows 9 and 10 indicate that the sequence 3-2 was followed by 1, nine times

and by 6, nine times; that is P(1|3-2) = 1/2 and P(6|3-2) = 1/2.

Table 5
Third-Order Probabilities (L = 1/3, M = 1/2, H = 2/3) and Frequencies (in parentheses) Inherent in the Sequences of Target Locations Across Every Two Blocks of Trials (Experiment 4)

Previous Target Locations	Next Target Location					
	1	2	3	4	5	6
3-2-1	--	--	L1 (3)	H1 (6)	--	--
4-2-1	--	--	L1 (3)	H1 (6)	--	--
3-5-1	--	--	H1 (6)	L1 (3)	--	--
4-5-1	--	--	H1 (6)	L1 (3)	--	--
3-2-6	--	--	H1 (6)	L1 (3)	--	--
4-2-6	--	--	H1 (6)	L1 (3)	--	--
3-5-6	--	--	L1 (3)	H1 (6)	--	--
4-5-6	--	--	L1 (3)	H1 (6)	--	--
1-3-2	M (6)	--	--	--	--	M (6)
6-3-2	M (3)	--	--	--	--	M (3)
1-4-2	M (3)	--	--	--	--	M (3)
6-4-2	M (6)	--	--	--	--	M (6)
1-3-5	M (3)	--	--	--	--	M (3)
6-3-5	M (6)	--	--	--	--	M (6)
1-4-5	M (6)	--	--	--	--	M (6)
6-4-5	M (3)	--	--	--	--	M (3)
2-1-3	--	H2 (4)	--	--	L2 (2)	--
5-1-3	--	H2 (8)	--	--	L2 (4)	--
2-6-3	--	L2 (4)	--	--	H2 (8)	--
5-6-3	--	L2 (2)	--	--	H2 (4)	--
2-1-4	--	L2 (4)	--	--	H2 (8)	--
5-1-4	--	L2 (2)	--	--	H2 (4)	--
2-6-4	--	H2 (4)	--	--	L2 (2)	--
5-6-4	--	H2 (8)	--	--	L2 (4)	--

Note. Dashes indicate that transitions did not occur. L1 = low probability transition from Set 1; H1 = high probability transition from Set 1; L2 = low probability transition from Set 2; H2 = high probability transition from Set 2.

The sequential structure was controlled so that certain types of information were not confounded with second-order probability. First-order probabilities were 1/2 (e.g., P(3|1) = P(4|1) = 1/2). Also, each location was a target location equally often (i.e., P(1) = P(2) = ... = P(6) = 1/6), lag 2 probabilities were 0.50 (e.g., P(3|2-x) = 0.50), and lag 3

probabilities and probabilities of the form $P(E|A_2\text{-}x\text{-}A_1)$ and $P(E|A_2\text{-}A_1\text{-}x)$ were 0.44, 0.50, or 0.56 (e.g., $P(3|4\text{-}x\text{-}x) = 0.50$, $P(2|2\text{-}x\text{-}4) = 0.44$, and $P(5|2\text{-}1\text{-}x) = 0.56$). Thus shorter reaction times on H than L transitions would be evidence for learning of the second-order probabilities, although learning of third-order probabilities cannot be ruled out as these were completely confounded with second-order probability (e.g., $P(3|2\text{-}1) = P(3|3\text{-}2\text{-}1) = 1/3$).

For each participant and each successive pair of blocks of trials, the sequence of target locations was generated by submitting the frequencies in Table 5 to a sequence-generation algorithm (Remillard & Clark, 1999). The algorithm randomly generated a 219-element sequence with the specified frequencies. Elements 1-110 and 110-219 each comprised a block of 110 trials. For the practice block of 99 trials at the beginning of session 1, the frequencies in Table 5 were replaced with the number 2. Thus the sequence of target locations in the practice block was unstructured in that first-, second-, and third-order probabilities were 1/2.

To counterbalance sequences (e.g., 3-2-1-3) across L, H, and M transitions, six versions of Table 5 were created. The six versions appear in Appendix C.

Awareness Questionnaire

The questionnaire to assess awareness of the second-order probabilities consisted of 12 items with two options per item (see Appendix D). For each item, numbers represented target locations and participants had to choose the high-probability transition. For example, item 1 required participants to indicate, by circling one of the two numbers 3 or 4, whether the double-dash (--), after appearing in locations 2 and then 1, was more likely to appear in location 3 or location 4 next. Eight items pertained to L/H transitions

and four to M transitions. For example, with respect to Table 5, item 1 corresponded to an L/H transition. Scores greater than 50% correct (random guessing performance) on the eight items pertaining to L/H transitions would indicate awareness of the second-order probabilities. For reference while participants completed the questionnaire, the six target locations on the monitor were marked with the bigram xx.

<div align="center">Results and Discussion</div>

For each participant, the median reaction time of correct responses was determined as a function of transition (L, H), set (1, 2), run completed (EE, UE, EU, UU), session (1-4), and condition (Present, Absent). Figure 4 shows reaction time, averaged across set and run, as a function of transition, session, and condition. Table 6 shows reaction time, averaged across transition and set, as a function of run, session, and condition. ANOVAs were as in Experiment 1 except that session had 4 levels and presence (Present, Absent) was a within-participants factor.

Present Condition

The effect of transition was significant, $F(1, 11) = 3.53$, $MSE = 1,304.50$, $p = .044$, whereas the Transition x Session-L interaction was not, $F(1, 11) = .00$, $MSE = 395.47$, $p = .956$. Thus reaction time was shorter on H than L transitions. This indicates learning of the second-order probabilities.

The First x Last interaction was significant, $F(1, 11) = 22.95$, $MSE = 917.97$, $p = .001$, reflecting the shorter reaction times on EE than UE runs and longer reaction times on EU than UU runs. Thus priming effects were present. The First x Last x Session-L interaction was also significant, $F(1, 11) = 6.07$, $MSE = 328.55$, $p = .031$, reflecting the decrease in reaction time differences between runs across sessions. The preceding

interactions did not interact significantly with transition, two *ps* > .380.
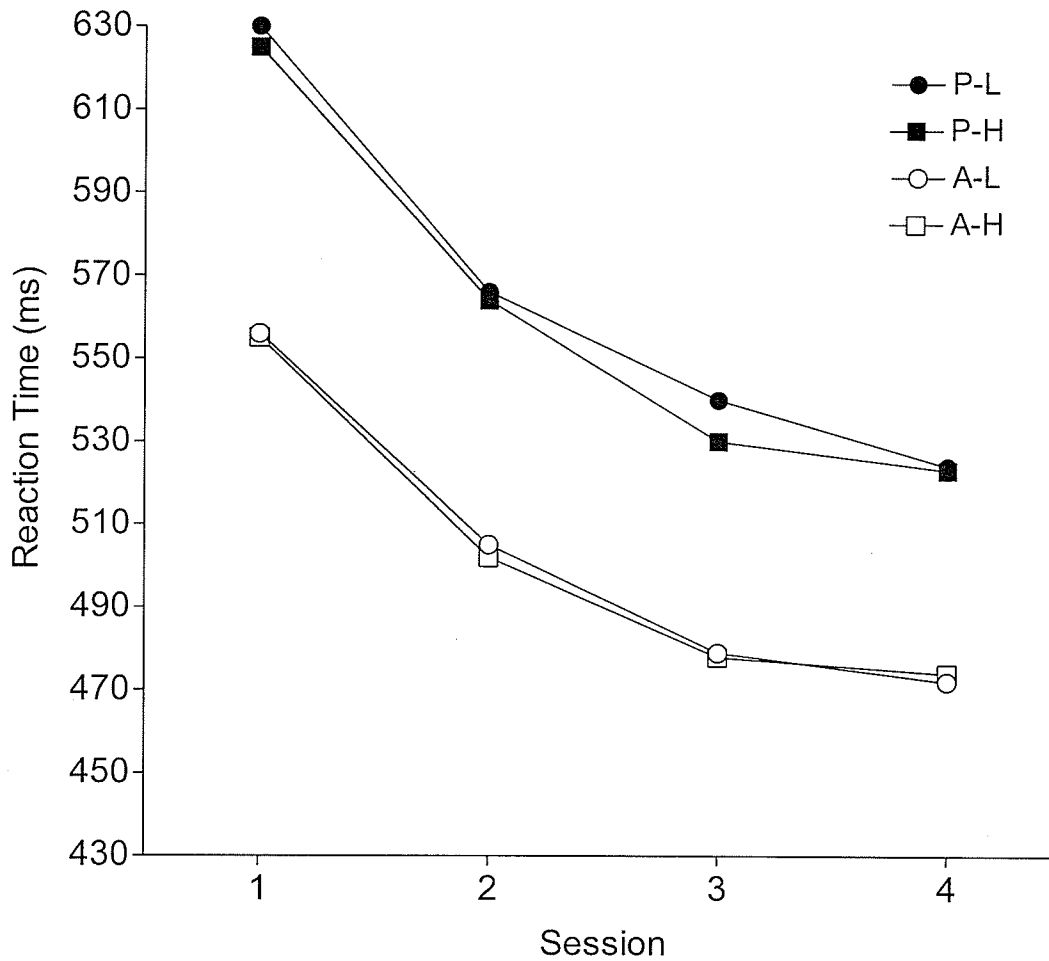
Figure 4. Reaction time, averaged across set (1, 2) and run (EE, UE, EU, UU), as a function of transition (L, H), session (1-4), and condition (Present, Absent) in Experiment 4. P = Present condition; A = Absent condition; L = low probability transition; H = high probability transition.

Table 6
Reaction Time (ms), Averaged Across Transition (L, H) and Set (1, 2), as a Function of Run (EE, UE, EU, UU), Session (1-4), and Condition (Present, Absent) in Experiment 4

	Present					Absent				
	Session					Session				
Run	1	2	3	4	Mean	1	2	3	4	Mean
EE	622	556	530	527	559	555	505	480	475	504
UE	629	573	541	533	569	559	505	482	475	505
EU	641	570	541	518	568	556	502	475	474	502
UU	622	561	529	516	557	553	504	477	467	500

Absent Condition

The effect of transition was not significant, $F(1, 11) = 2.56$, $MSE = 55.44$, $p = .069$, nor was the Transition x Session-L interaction, $F(1, 11) = .38$, $MSE = 474.05$, $p = .548$. Thus there was no evidence for shorter reaction times on H than L transitions.

The First x Last interaction, $F(1, 11) = 1.07$, $MSE = 303.12$, $p = .322$, and First x Last x Session-L interaction, $F(1, 11) = .07$, $MSE = 119.25$, $p = .802$, were not significant. Thus there was no evidence for priming effects. The preceding interactions did not interact significantly with transition, two $ps > .085$.

Present Versus Absent Condition

The Transition x Presence interaction approached significance, $F(1, 11) = 2.81$, $MSE = 556.66$, $p = .061$, whereas the Transition x Presence x Session-L interaction did not, $F(1, 11) = .21$, $MSE = 379.51$, $p = .659$. Thus the reaction time difference between L and H transitions was marginally greater in the Present than Absent condition. Assuming that knowledge of the second-order probabilities was equivalent in the two conditions, the result suggests that in the Present condition, participants processed, during the 400 ms interval, the bigram marking the high probability transition and prepared the

corresponding response.

Turning to the runs, the First x Last x Presence interaction was significant, $F(1, 11) = 16.97$, $MSE = 475.80$, $p = .002$, reflecting the greater reaction time difference between UE and EE runs and between EU and UU runs in the Present than Absent condition. Assuming that priming effects were equivalent in the two conditions, the result suggests that in the Present condition, participants processed, during the 400 ms interval, the bigram marking the primed target location (in the case of EE and EU runs) and prepared the corresponding response. The First x Last x Presence x Session-L interaction was not significant, $F(1, 11) = 3.76$, $MSE = 299.37$, $p = .078$.

Awareness of Second-Order Probabilities

On the awareness questionnaire, the percentage of the eight items pertaining to L/H transitions receiving correct responses (i.e., for which H transitions were chosen) was determined for each participant. The mean percent correct was 53.1% which did not differ significantly from what would be expected by random guessing on the questionnaire (50% correct), $F(1, 11) = .26$, $MSE = 458.10$, $p = .623$. Fifty-one and 45 of the 96 items (8 items x 12 participants) received correct and incorrect responses, respectively. These frequencies did not differ significantly from what would be expected by random guessing on the questionnaire (48 and 48, respectively), $X^2(1) = .375$, $p = .540$. Thus there was no evidence for awareness of the second-order probabilities.

Experiment 2 Versus Experiment 4

An examination of Figures 2 and 4 shows that the pattern of reaction time differences between L and H transitions in the Consistent group of Experiment 2 differed from that in the current experiment. ANOVAs with transition (L, H), set (1, 2), first (E,

U), last (E, U), and session (1, 2, 3) as within-participants factors and experiment (2, 4) and version (1-6) as between-participants factors were performed on the reaction time data from the Present and Absent conditions.

In the Present condition, the Transition x Experiment interaction, $F(1, 12) =$ 10.98, $MSE = 2,325.89, p = .006$, and Transition x Session-L x Experiment interaction, $F(1, 12) = 5.47, MSE = 1,025.65, p = .038$, were significant. Thus the reaction time difference between L and H transitions was greater in the Consistent group of Experiment 2 than in the current experiment and increased at a faster rate across sessions in the former than latter experiment.

In the Absent condition, the Transition x Experiment interaction, $F(1, 12) = 5.60$, $MSE = 723.04, p = .036$, and Transition x Session-L x Experiment interaction, $F(1, 12) =$ 11.04, $MSE = 417.67, p = .006$, were significant. Thus the reaction time difference between L and H transitions was greater in the Consistent group of Experiment 2 than in the current experiment and increased at a faster rate across sessions in the former than latter experiment.

The results suggest that learning in the Consistent group of Experiment 2 was not limited to second- or third-order probabilities (otherwise performance would have been similar to that in the current experiment) and therefore encompassed first-order probabilities.

GENERAL DISCUSSION

The current study provides strong evidence for pure perceptual-based learning of first-order probabilities. Using tightly controlled, probabilistically structured sequences of target locations where target location was not relevant for responding and the sequences

of targets and hence responses were unstructured and independent of the sequences of target locations, reaction time in the Present condition decreased with increasing first-order probability. Moreover, learning was implicit because there was no awareness of what was learned. On the awareness questionnaires, high-probability transitions were chosen no more often than low-probability transitions. The one exception was the No-Mask group in Experiment 3. However, awareness in that group did not seem to have an effect on the reaction time differences between L and H transitions, which were similar to those in other groups where there was no awareness of the first-order probabilities. Finally, there was some evidence for learning of second-order probabilities. However, the reaction time differences between L and H transitions in the Present condition of Experiment 4 were quite small and so a replication of the results would be necessary before concluding that pure perceptual-based learning of second-order probabilities is a reliable phenomenon.

The current study has also shown that large eye movements are not necessary for pure perceptual-based learning and that such learning can proceed with relatively small eye movements (e.g., footnote 4). This is consistent with the results of studies showing that people can implicitly learn the relationship between the form of a cue and the location of a subsequent target when target location is not relevant for responding and people are required not to move their eyes (Lambert, Naikar, McLachlan, & Aitken, 1999; Lambert & Sumich, 1996; also see Olson & Chun, 2001, Experiment 3).

As noted in the Introduction, the role of oculomotor programming in pure perceptual-based learning may be difficult to discount because the sudden appearance of a stimulus in the visual field, as occurs in the SRT task, may automatically program an

eye movement towards the stimulus. However, evidence that (a) pure perceptual-based learning can proceed with relatively small eye movements, together with evidence that (b) eye movements are normally preceded by shifts of visuospatial attention, (c) the mechanism for programming shifts of attention is independent of that for programming eye movements, and (d) the sudden appearance of a stimulus in the visual field, as occurs in the SRT task, automatically captures attention strongly suggests that automatic orienting of visuospatial attention is sufficient for pure perceptual-based learning. This in turn suggests that responding motorically or effortfully to events in a sequence is not necessary for learning the sequence of events, contrary to current hypotheses of implicit sequence learning. However, it is possible that responding motorically or effortfully to events in a sequence, while not necessary for learning the sequence of events, may enhance learning.

In the current study, reaction time differences between L and H transitions and between runs were larger in the Present than Absent condition, even when the two conditions were within-participants with evidence of transfer of first-order probability knowledge from the Present to Absent condition. Moreover, the results were not due to overall reaction time differences (and hence differences in difficulty) between conditions nor to forward masking in the Absent condition.[6] Thus the most straightforward explanation is that in the Present condition, participants processed, during the 400 ms interval before the underline appeared, the bigram marking the high probability transition (or primed target location in the case of EE and EU runs) and prepared the corresponding response. Such preparation presumably produced reaction time benefits when the line appeared below the bigram marking the high probability transition (or primed target

location in the case of EE runs) and costs when it appeared below the different bigram marking the low probability transition (or unprimed target location in the case of EU runs). This indicates that the mechanisms underlying pure perceptual-based learning and priming both afford processing of information at an anticipated target location before a cue (e.g., underline) is presented. What is unknown is the time course of orienting from the current target location to an anticipated target location and processing information located there. Future studies manipulating the time interval between bigram-ordering and underlining of the target bigram might shed light on the time course of orienting.

Learning and Priming: A Common Mechanism?

The learning and priming mechanisms share a number of characteristics that suggest they may be related. First, both mechanisms operate on visuospatial locations. Second, both mechanisms afford processing of information at anticipated target locations. Third, both mechanisms failed to produce significant effects in a pilot study that was identical to the Consistent group of Experiment 2 except that the bigrams xo, ox, mn, and nm were replaced with the uppercase letters C, O, M, and N, respectively, and adjacent target locations were separated by 0.4 cm rather than 1.1 cm. The letters were each 0.3 cm in width and 0.5 cm in height. In the pilot study, there was no evidence for first-order probability learning nor for priming.[7]

Fourth and finally, learning of second-order probabilities was impaired relative to learning of first-order probabilities. Second-order probability information is more complex than first-order probability information because in the former, the preceding two target locations are needed to differentially predict the next target location whereas in the latter, only the preceding target location is required. That the priming mechanism shares a

similar characteristic would be evidenced by impaired priming associated with the repetition of a trigram (e.g., 3-2-1 in the run 3-2-1-3-2-1) relative to priming associated with the repetition of a bigram (e.g., 2-1 in the run 2-1-3-2-1). In the former case, the preceding two target locations prime the next target location (e.g., following 3-2-1, a subsequent 3-2 primes 1) whereas in the latter case, the preceding target location primes the next target location (e.g., following 2-1-3, a subsequent 2 primes 1).

To examine priming associated with trigrams and bigrams, eight types of six-element runs were defined by whether the first and fourth, second and fifth, and third and sixth elements were equal (E) or unequal (U) (see Table 7). For example, 4-5-1-3-2-1 is a UUE run because the first and fourth elements are unequal (U), the second and fifth elements are unequal (U), and the third and sixth elements are equal (E). If there is

Table 7
Types of Six-Element Runs

Run	Example
EEE	3-2-1-3-2-1
UEE	4-2-1-3-2-1
EUE	3-5-1-3-2-1
UUE	4-5-1-3-2-1
EEU	3-2-6-3-2-1
UEU	4-2-6-3-2-1
EUU	3-5-6-3-2-1
UUU	4-5-6-3-2-1

Note. Six-element runs were categorized as a function of the first and fourth, second and fifth, and third and sixth elements being equal (E) or unequal (U).

priming associated with trigrams, reaction time to the last element should be shorter for EEE runs, where repetition of a trigram is correctly primed (e.g., 3-2-1-3-2 primes 1 and 1 occurs), than for UEE runs and longer for EEU runs, where repetition of a trigram is

incorrectly primed (e.g., 3-2-6-3-2 primes 6 but 1 occurs), than for UEU runs. Priming associated with trigrams was quantified as $(RT_{UEE} - RT_{EEE}) + (RT_{EEU} - RT_{UEU})$. If there is priming associated with bigrams, reaction time to the last element should be shorter for EEE and UEE runs, where repetition of a bigram is correctly primed (e.g., 2-1-3-2 primes 1 and 1 occurs), than for EUE and UUE runs and longer for EEU and UEU runs, where repetition of a bigram is incorrectly primed (e.g., 2-6-3-2 primes 6 but 1 occurs), than for EUU and UUU runs. Priming associated with bigrams was quantified as [(the mean of RT_{EUE} and RT_{UUE}) - (the mean of RT_{EEE} and RT_{UEE})] + [(the mean of RT_{EEU} and RT_{UEU}) - (the mean of RT_{EUU} and RT_{UUU})].

For each participant in the various experiments of the present study, the median reaction time of correct responses was determined as a function of run completed (see Table 7) and transition (L1, H1, L2, H2, M; see Table 2). To obtain a sufficient number of observations, the data from a number of sessions in an experiment were combined. Averaging across transition, priming effects associated with bigrams and trigrams were calculated using the equations described in the preceding paragraph. The priming effects appear in Table 8. Overall, the results suggest that in the Present condition, priming associated with trigrams was impaired relative to priming associated with bigrams. This is consistent with results from Remillard and Clark (2001) that also suggest that priming associated with trigrams is impaired relative to priming associated with bigrams.

If learning and priming are subserved by the same mechanism, then any mechanistic account of pure perceptual-based learning would have to explain the learning and priming effects observed in the current study. These effects are summarized in Figure 5 which shows session 3 reaction time, averaged across group (Consistent, Difficult, No-

Mask) and set (1, 2), as a function of transition (L, H), run completed (EE, UE, EU, UU),

and condition (Present, Absent).

Table 8
Priming Effects (in ms) Associated with Bigrams and Trigrams

Experiment	Condition	Bigrams	Trigrams	Difference
1[a]	Present	18*	4	14+
	Absent	7*	-2	9*
2 & 3[b]	Present	16*	8*	8*
	Absent	4*	2	2
4[c]	Present	13*	3	10
	Absent	2	0	2

Note. Statistical tests determined whether priming effects were significantly different from zero.
[a]The data are from sessions 2 and 3 combined. [b]The data are from sessions 1-3 combined and collapsed across the Consistent, Difficult, and No-Mask groups. Priming effects did not vary significantly as a function of group, all *p*s > .16. [c]The data are from sessions 2-4 combined.
*p < .05. +.05 < p < .10.

It is interesting that robust first-order probability learning in session 3 could not

overcome priming. In fact, first-order probability learning did not seem to have an effect

on priming. Reaction time differences between UE and EE runs and between EU and UU

runs in session 3 were similar to those in Experiment 4 (see Table 6) where learning of

first-order probabilities was not possible and learning of second-order probabilities was

considerably impaired relative to learning of first-order probabilities. This, coupled with

the fact that reaction time differences between runs were identical for L and H transitions,

suggests that learning and priming effects were additive. This is consistent with results

from Remillard and Clark (2001) that also suggest that learning and priming effects are

additive (also see Koch, 2001, Experiments 1 & 2). In addition to the effects shown in

Figure 5, a mechanistic account of pure perceptual-based learning would also have to

explain why learning of second-order probabilities is impaired relative to learning of first-

order probabilities and why priming associated with trigrams is impaired relative to

priming associated with bigrams.
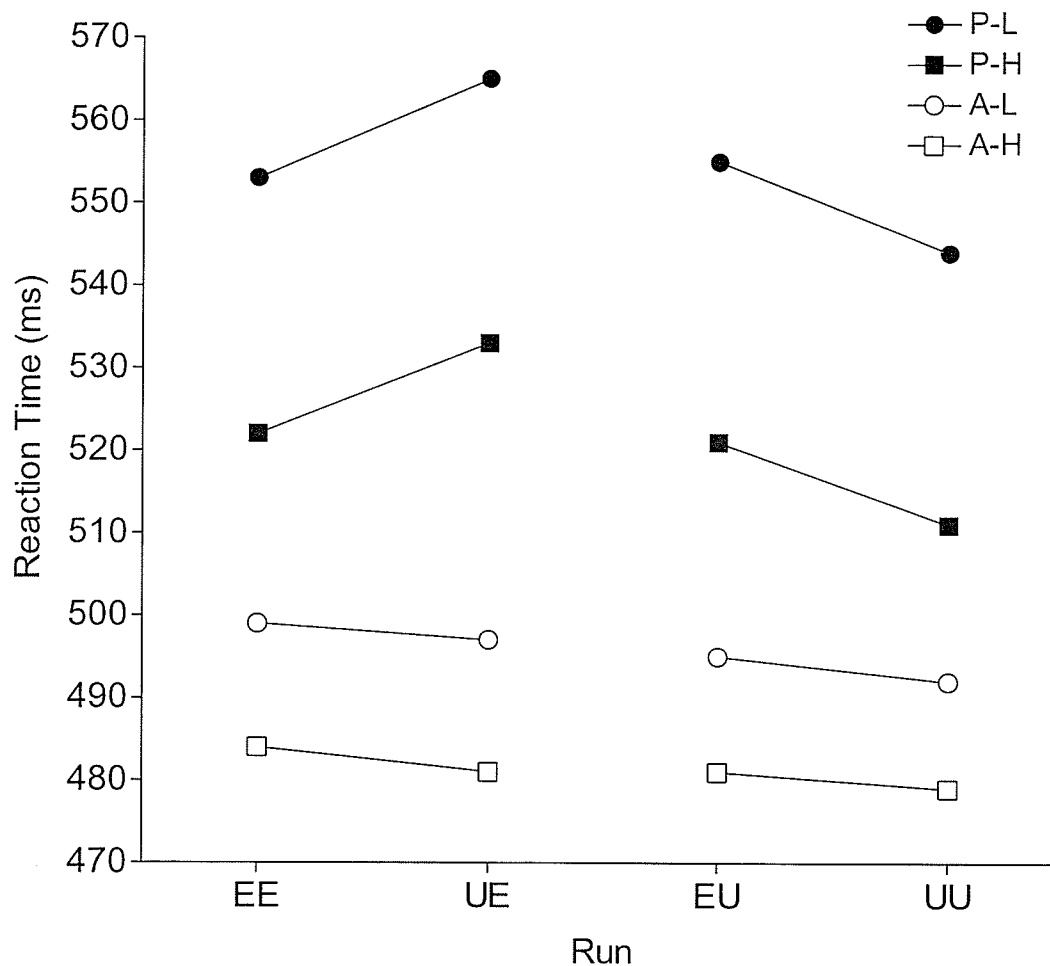
Figure 5. Session 3 reaction time, averaged across group (Consistent, Difficult, No-Mask) and set (1, 2), as a function of transition (L, H), run completed (EE, UE, EU, UU), and condition (Present, Absent). P = Present condition; A = Absent condition; L = low probability transition; H = high probability transition.

Comparisons with Remillard and Clark (2001)

It is informative to compare the results from the Present conditions of the current study with the results of a study by Remillard and Clark (2001, Experiments 3 & 4). The latter study was similar to the current study except that participants responded to the location of the target with a corresponding keypress and first- and second-order probabilities were .40 versus .50. Session 3 reaction time differences between L and H transitions were approximately 38 ms and 17 ms for first- and second-order probabilities, respectively in Remillard and Clark, and 37 ms and 10 ms, respectively in the current study. Although reaction time differences were similar in the two studies, transition probabilities were narrower in Remillard and Clark (.40 versus .60) than in the current study (.33 versus .67). This suggests that if transition probabilities had been similar in the two studies, reaction time differences between L and H transitions would have been greater in Remillard and Clark than in the current study.

One explanation for the extrapolated differences between the two studies is that learning in Remillard and Clark (2001) was to some extent response-based. The sequence of target locations was correlated with the sequence of response locations and so learning may have involved the sequence of response locations. Response-based learning was not possible in the current study.

Alternatively, learning in Remillard and Clark (2001) may have been mostly perceptual-based (i.e., involved only the sequence of target locations) and there was greater learning because of more effortful processing of target location. Target location was relevant for responding in Remillard and Clark but not in the current study.

Finally, learning of first- and second-order probabilities may have been equivalent

in the two studies, but the Remillard and Clark (2001) study was more sensitive to such learning because of greater response preparation. Each target location was associated with a single, compatibly-mapped response and so knowing where the target was most likely to appear next could readily lead to preparation of the corresponding response. In contrast, the current study required that the bigram marking the anticipated target location be processed and the corresponding, noncompatibly-mapped response prepared.

Thus there are three possible explanations for the extrapolated differences between the Remillard and Clark (2001) study and the current study. Determining which possibilities are correct would further our understanding of response-based learning and of the effects of effortful processing of target location on perceptual-based learning.

Conclusion

The current study has shown that people can implicitly learn the relationship between preceding target locations and the location of the target's next appearance. Prior research has also shown that people can implicitly learn the relationship between the form of a cue and the location of a subsequent target (Lambert et al., 1999; Lambert & Sumich, 1996; Peterson, 1999; also see Olson & Chun, 2001, Experiment 3) and between the global layout of a scene and the location of a target embedded in the scene (Chun & Jiang, 1998, 1999, Experiment 2; Jiang & Chun, 2001). Thus when people are required to detect and respond to a visual target, they will implicitly learn relationships in the environment that are helpful in predicting the visuospatial location of the target. Understanding the mechanisms underlying pure perceptual-based learning could elucidate how such relationships are learned.

The focus of the present study was pure perceptual-based learning where the

sequence of interest was one of target locations. Future research could examine whether people can implicitly learn a sequence of nonspatial stimuli when the sequence is uncorrelated with a sequence of responses and the nonspatial stimuli are not relevant for responding. There is some evidence that this is possible when the nonspatial stimuli are auditorily presented letters (Goschke, 1998, pp. 416-419; Goschke et al., 2001), location/color combinations (Heuer, Schmidtke, & Kleinsorge, 2001), graphic symbols (Koch, 2001), or event durations (Olson & Chun, 2001), but not when they are visually presented colors (Kelly & Burton, 2001) or time intervals (Shin & Ivry, 2002). The reasons for the discrepant findings are not clear. One possibility is differences in effortful processing of the stimuli. With the exception of the Olson & Chun (2001) study, all of the studies yielding positive results required participants to effortfully process the stimuli in order to generate a response even though the stimuli themselves were not the target of the response. In contrast, effortful processing of stimuli was not necessary to generate a response in the two studies obtaining negative results. Thus unlike with spatial stimuli, implicitly learning a sequence of nonspatial stimuli may require effortful processing of the stimuli.

Implicit Learning of Transition Probabilities

The current study examined implicit learning of transition probabilities (also see Remillard & Clark, 2001). Such learning is important for a number of reasons. First, as alluded to in the introduction (see Probabilistic versus Deterministic Sequences), implicit learning of transition probabilities may underlie implicit learning of deterministic sequences and hence implicit sequence learning in general. Second, implicit learning of transition probabilities may underlie some aspects of language processing. One

connectionist model that has been successful at modelling human performance on SRT

tasks and which essentially learns transition probabilities (Cleeremans, 1993; Cleeremans

& Jimenez, 1998; Jimenez et al., 1996) has also been successful in the realm of language

processing. When presented with sentences generated by a grammar, the model not only

learns which words in the lexicon can legally follow the current word in the sentence

given the sentence context up to that point, but it also learns how likely these words are to

follow (Elman, 1990, 1991). This is consistent with studies showing that people do

possess knowledge of transition probabilities in English. For example, given the

preceding sentence context, words having high transition probabilities are recognized

more quickly than words having low transition probabilities (Grosjean, 1980; Morton &

Long, 1976). Interestingly, the model learns a complex grammar only if its "memory

capacity" starts small and is gradually increased (Elman, 1993). This closely resembles

the conditions under which children learn language.

The model simulates human language performance in other respects as well. For

example, like humans, the model has a greater difficulty processing sentences involving

center embeddings and cross-dependencies than sentences involving right branchings

(Christiansen & Chater, 1999). The model can also simulate French children's acquisition

of orthographic regularities regarding the doubling of letters in written language (Pacton,

Perruchet, Fayol, & Cleeremans, 2001).

Another line of evidence for a role of transition probability learning in language

processing comes from studies showing that 8-month-old infants are capable of learning

transition probabilities (Aslin, Saffran, & Newport, 1998). It has been argued that such

learning may help infants segment words from a continuous speech stream (Aslin,

Saffran, & Newport, 1998; Saffran, Newport, Aslin, et al., 1997). Apparently, pairs of syllables that occur within words have higher transition probabilities than pairs of syllables that span word boundaries and infants may use such cues to discover word boundaries. Consistent with this view, the connectionist model outlined above can learn to delineate word boundaries when presented with a long string of letters made up of concatenated words (Elman, 1990).

A final line of evidence for a role of transition probability learning in language processing is that both sequence learning in SRT tasks (which presumably involves learning of transition probabilities) and language processing may share similar neural structures. For example, the basal ganglia appear to play an important role in the application of syntactic and grammatical rules (Lieberman, Kako, Friedman, et al., 1992; Ullman, Corkin, Coppola, et al., 1997) and in the learning of sequences in SRT tasks (Jackson, Jackson, Harrison, et al., 1995; Peigneux, Maquet, Meulemans, et al., 2000; Rauch, Whalen, Savage, et al., 1997; Vakil et al., 2000; Westwater, McDowall, Seigert, et al., 1998; Willingham & Koroshetz, 1993). Similarly, Broca's area may be involved in learning sequences of language-related material in SRT tasks. Patients with Broca's aphasia cannot learn a repeating sequence of auditorily presented letters in an SRT task but can learn a repeating spatiomotor sequence (Goschke et al., 2001). This result also suggests that different cognitive or brain systems may be involved in learning different kinds of sequences in SRT tasks (also see, Frensch, 1998, pp. 87-95; Helmuth et al., 2000; Mayr, 1996).

A final reason why implicit learning of transition probabilities is important is that it may underlie social intuition. Lieberman (2000, p. 111) defines intuition as "the

subjective experience of a mostly nonconscious process that is fast, a-logical, and inaccessible to consciousness that, dependent on exposure to the domain or problem space, is capable of extracting probabilistic contingencies [e.g., transition probabilities]." Lieberman argues that certain forms of social intuition are the result of implicit sequence learning (again, which presumably involves the learning of transition probabilities). Specifically, people implicitly learn sequences of behavioral cues and what they mean and intuition is the unconscious use of such knowledge. According to Lieberman, decoding (or intuitive social cognition) is the formation of intuitive judgments about a person's thoughts, feelings, or subsequent actions that are based on sequences of behavioral cues exhibited by that person. In contrast, encoding (or intuituve social action) is the production of sequences of behavioral cues by an individual that reflect the individual's mental state.

The preceding discussion makes it clear that implicit learning of transition probabilities may underlie many important forms of behavior that involve learning sequentially and temporally organized material. Consequently, understanding the mechanism(s) subserving implicit learning of transition probabilities is crucial to a deeper understanding of human behavior. As a step in that direction, the present study has shown that people can implicitly learn first-order transition probabilities embedded in a sequence of target locations and that such learning (a) affords processing of information at an anticipated target location, (b) requires neither motor responding to nor effortful processing of target location, and (c) may be subserved by a mechanism similar to that underlying priming. The present study has also shown that implicit learning of second-order transition probabilities is impaired relative to implicit learning of first-order

probabilities. Future studies should extend the current results so as to further characterize

the learning mechanism(s).

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APPENDIX A

The Six Versions of Table 2

Version 1

Previous Target Locations	Next Target Location					
	1	2	3	4	5	6
3-2-1	--	--	L1 (4)	H1 (8)	--	--
4-2-1	--	--	L1 (2)	H1 (4)	--	--
3-5-1	--	--	L1 (2)	H1 (4)	--	--
4-5-1	--	--	L1 (4)	H1 (8)	--	--
3-2-6	--	--	H1 (8)	L1 (4)	--	--
4-2-6	--	--	H1 (4)	L1 (2)	--	--
3-5-6	--	--	H1 (4)	L1 (2)	--	--
4-5-6	--	--	H1 (8)	L1 (4)	--	--
1-3-2	M (4)	--	--	--	--	M (4)
6-3-2	M (8)	--	--	--	--	M (8)
1-4-2	M (4)	--	--	--	--	M (4)
6-4-2	M (2)	--	--	--	--	M (2)
1-3-5	M (2)	--	--	--	--	M (2)
6-3-5	M (4)	--	--	--	--	M (4)
1-4-5	M (8)	--	--	--	--	M (8)
6-4-5	M (4)	--	--	--	--	M (4)
2-1-3	--	H2 (4)	--	--	L2 (2)	--
5-1-3	--	H2 (4)	--	--	L2 (2)	--
2-6-3	--	H2 (8)	--	--	L2 (4)	--
5-6-3	--	H2 (8)	--	--	L2 (4)	--
2-1-4	--	L2 (4)	--	--	H2 (8)	--
5-1-4	--	L2 (4)	--	--	H2 (8)	--
2-6-4	--	L2 (2)	--	--	H2 (4)	--
5-6-4	--	L2 (2)	--	--	H2 (4)	--

Version 2

Previous Target Locations	Next Target Location					
	1	2	3	4	5	6
3-2-1	--	--	H1 (4)	L1 (2)	--	--
4-2-1	--	--	H1 (8)	L1 (4)	--	--
3-5-1	--	--	H1 (8)	L1 (4)	--	--
4-5-1	--	--	H1 (4)	L1 (2)	--	--
3-2-6	--	--	L1 (2)	H1 (4)	--	--
4-2-6	--	--	L1 (4)	H1 (8)	--	--
3-5-6	--	--	L1 (4)	H1 (8)	--	--
4-5-6	--	--	L1 (2)	H1 (4)	--	--
1-3-2	M (4)	--	--	--	--	M (4)
6-3-2	M (2)	--	--	--	--	M (2)
1-4-2	M (4)	--	--	--	--	M (4)
6-4-2	M (8)	--	--	--	--	M (8)
1-3-5	M (8)	--	--	--	--	M (8)
6-3-5	M (4)	--	--	--	--	M (4)
1-4-5	M (2)	--	--	--	--	M (2)
6-4-5	M (4)	--	--	--	--	M (4)
2-1-3	--	L2 (4)	--	--	H2 (8)	--
5-1-3	--	L2 (4)	--	--	H2 (8)	--
2-6-3	--	L2 (2)	--	--	H2 (4)	--
5-6-3	--	L2 (2)	--	--	H2 (4)	--
2-1-4	--	H2 (4)	--	--	L2 (2)	--
5-1-4	--	H2 (4)	--	--	L2 (2)	--
2-6-4	--	H2 (8)	--	--	L2 (4)	--
5-6-4	--	H2 (8)	--	--	L2 (4)	--

Version 3

Previous Target Locations	Next Target Location					
	1	2	3	4	5	6
3-2-1	--	--	M (4)	M (4)	--	--
4-2-1	--	--	M (8)	M (8)	--	--
3-5-1	--	--	M (4)	M (4)	--	--
4-5-1	--	--	M (2)	M (2)	--	--
3-2-6	--	--	M (2)	M (2)	--	--
4-2-6	--	--	M (4)	M (4)	--	--
3-5-6	--	--	M (8)	M (8)	--	--
4-5-6	--	--	M (4)	M (4)	--	--
1-3-2	H2 (4)	--	--	--	--	L2 (2)
6-3-2	H2 (4)	--	--	--	--	L2 (2)
1-4-2	H2 (8)	--	--	--	--	L2 (4)
6-4-2	H2 (8)	--	--	--	--	L2 (4)
1-3-5	L2 (4)	--	--	--	--	H2 (8)
6-3-5	L2 (4)	--	--	--	--	H2 (8)
1-4-5	L2 (2)	--	--	--	--	H2 (4)
6-4-5	L2 (2)	--	--	--	--	H2 (4)
2-1-3	--	L1 (4)	--	--	H1 (8)	--
5-1-3	--	L1 (2)	--	--	H1 (4)	--
2-6-3	--	L1 (2)	--	--	H1 (4)	--
5-6-3	--	L1 (4)	--	--	H1 (8)	--
2-1-4	--	H1 (8)	--	--	L1 (4)	--
5-1-4	--	H1 (4)	--	--	L1 (2)	--
2-6-4	--	H1 (4)	--	--	L1 (2)	--
5-6-4	--	H1 (8)	--	--	L1 (4)	--

Version 4

Previous Target Locations	Next Target Location					
	1	2	3	4	5	6
3-2-1	--	--	M (4)	M (4)	--	--
4-2-1	--	--	M (2)	M (2)	--	--
3-5-1	--	--	M (4)	M (4)	--	--
4-5-1	--	--	M (8)	M (8)	--	--
3-2-6	--	--	M (8)	M (8)	--	--
4-2-6	--	--	M (4)	M (4)	--	--
3-5-6	--	--	M (2)	M (2)	--	--
4-5-6	--	--	M (4)	M (4)	--	--
1-3-2	L2 (4)	--	--	--	--	H2 (8)
6-3-2	L2 (4)	--	--	--	--	H2 (8)
1-4-2	L2 (2)	--	--	--	--	H2 (4)
6-4-2	L2 (2)	--	--	--	--	H2 (4)
1-3-5	H2 (4)	--	--	--	--	L2 (2)
6-3-5	H2 (4)	--	--	--	--	L2 (2)
1-4-5	H2 (8)	--	--	--	--	L2 (4)
6-4-5	H2 (8)	--	--	--	--	L2 (4)
2-1-3	--	H1 (4)	--	--	L1 (2)	--
5-1-3	--	H1 (8)	--	--	L1 (4)	--
2-6-3	--	H1 (8)	--	--	L1 (4)	--
5-6-3	--	H1 (4)	--	--	L1 (2)	--
2-1-4	--	L1 (2)	--	--	H1 (4)	--
5-1-4	--	L1 (4)	--	--	H1 (8)	--
2-6-4	--	L1 (4)	--	--	H1 (8)	--
5-6-4	--	L1 (2)	--	--	H1 (4)	--

Version 5

Previous Target Locations	Next Target Location					
	1	2	3	4	5	6
3-2-1	--	--	H2 (4)	L2 (2)	--	--
4-2-1	--	--	H2 (4)	L2 (2)	--	--
3-5-1	--	--	H2 (8)	L2 (4)	--	--
4-5-1	--	--	H2 (8)	L2 (4)	--	--
3-2-6	--	--	L2 (4)	H2 (8)	--	--
4-2-6	--	--	L2 (4)	H2 (8)	--	--
3-5-6	--	--	L2 (2)	H2 (4)	--	--
4-5-6	--	--	L2 (2)	H2 (4)	--	--
1-3-2	L1 (4)	--	--	--	--	H1 (8)
6-3-2	L1 (2)	--	--	--	--	H1 (4)
1-4-2	L1 (2)	--	--	--	--	H1 (4)
6-4-2	L1 (4)	--	--	--	--	H1 (8)
1-3-5	H1 (8)	--	--	--	--	L1 (4)
6-3-5	H1 (4)	--	--	--	--	L1 (2)
1-4-5	H1 (4)	--	--	--	--	L1 (2)
6-4-5	H1 (8)	--	--	--	--	L1 (4)
2-1-3	--	M (4)	--	--	M (4)	--
5-1-3	--	M (8)	--	--	M (8)	--
2-6-3	--	M (4)	--	--	M (4)	--
5-6-3	--	M (2)	--	--	M (2)	--
2-1-4	--	M (2)	--	--	M (2)	--
5-1-4	--	M (4)	--	--	M (4)	--
2-6-4	--	M (8)	--	--	M (8)	--
5-6-4	--	M (4)	--	--	M (4)	--

Version 6

Previous Target Locations	Next Target Location					
	1	2	3	4	5	6
3-2-1	--	--	L2 (4)	H2 (8)	--	--
4-2-1	--	--	L2 (4)	H2 (8)	--	--
3-5-1	--	--	L2 (2)	H2 (4)	--	--
4-5-1	--	--	L2 (2)	H2 (4)	--	--
3-2-6	--	--	H2 (4)	L2 (2)	--	--
4-2-6	--	--	H2 (4)	L2 (2)	--	--
3-5-6	--	--	H2 (8)	L2 (4)	--	--
4-5-6	--	--	H2 (8)	L2 (4)	--	--
1-3-2	H1 (4)	--	--	--	--	L1 (2)
6-3-2	H1 (8)	--	--	--	--	L1 (4)
1-4-2	H1 (8)	--	--	--	--	L1 (4)
6-4-2	H1 (4)	--	--	--	--	L1 (2)
1-3-5	L1 (2)	--	--	--	--	H1 (4)
6-3-5	L1 (4)	--	--	--	--	H1 (8)
1-4-5	L1 (4)	--	--	--	--	H1 (8)
6-4-5	L1 (2)	--	--	--	--	H1 (4)
2-1-3	--	M (4)	--	--	M (4)	--
5-1-3	--	M (2)	--	--	M (2)	--
2-6-3	--	M (4)	--	--	M (4)	--
5-6-3	--	M (8)	--	--	M (8)	--
2-1-4	--	M (8)	--	--	M (8)	--
5-1-4	--	M (4)	--	--	M (4)	--
2-6-4	--	M (2)	--	--	M (2)	--
5-6-4	--	M (4)	--	--	M (4)	--

APPENDIX B

The Awareness Questionnaire of Experiments 1-3

```
              3
1  --->
              4


              3
6  --->
              4


              1
2  --->
              6


              1
5  --->
              6


              2
3  --->
              5


              2
4  --->
              5
```

APPENDIX C

The Six Versions of Table 5

Version 1

Previous Target Locations	Next Target Location					
	1	2	3	4	5	6
3-2-1	--	--	L1 (3)	H1 (6)	--	--
4-2-1	--	--	L1 (3)	H1 (6)	--	--
3-5-1	--	--	H1 (6)	L1 (3)	--	--
4-5-1	--	--	H1 (6)	L1 (3)	--	--
3-2-6	--	--	H1 (6)	L1 (3)	--	--
4-2-6	--	--	H1 (6)	L1 (3)	--	--
3-5-6	--	--	L1 (3)	H1 (6)	--	--
4-5-6	--	--	L1 (3)	H1 (6)	--	--
1-3-2	M (6)	--	--	--	--	M (6)
6-3-2	M (3)	--	--	--	--	M (3)
1-4-2	M (3)	--	--	--	--	M (3)
6-4-2	M (6)	--	--	--	--	M (6)
1-3-5	M (3)	--	--	--	--	M (3)
6-3-5	M (6)	--	--	--	--	M (6)
1-4-5	M (6)	--	--	--	--	M (6)
6-4-5	M (3)	--	--	--	--	M (3)
2-1-3	--	H2 (4)	--	--	L2 (2)	--
5-1-3	--	H2 (8)	--	--	L2 (4)	--
2-6-3	--	L2 (4)	--	--	H2 (8)	--
5-6-3	--	L2 (2)	--	--	H2 (4)	--
2-1-4	--	L2 (4)	--	--	H2 (8)	--
5-1-4	--	L2 (2)	--	--	H2 (4)	--
2-6-4	--	H2 (4)	--	--	L2 (2)	--
5-6-4	--	H2 (8)	--	--	L2 (4)	--

Version 2

Previous Target Locations	Next Target Location					
	1	2	3	4	5	6
3-2-1	--	--	H1 (6)	L1 (3)	--	--
4-2-1	--	--	H1 (6)	L1 (3)	--	--
3-5-1	--	--	L1 (3)	H1 (6)	--	--
4-5-1	--	--	L1 (3)	H1 (6)	--	--
3-2-6	--	--	L1 (3)	H1 (6)	--	--
4-2-6	--	--	L1 (3)	H1 (6)	--	--
3-5-6	--	--	H1 (6)	L1 (3)	--	--
4-5-6	--	--	H1 (6)	L1 (3)	--	--
1-3-2	M (3)	--	--	--	--	M (3)
6-3-2	M (6)	--	--	--	--	M (6)
1-4-2	M (6)	--	--	--	--	M (6)
6-4-2	M (3)	--	--	--	--	M (3)
1-3-5	M (6)	--	--	--	--	M (6)
6-3-5	M (3)	--	--	--	--	M (3)
1-4-5	M (3)	--	--	--	--	M (3)
6-4-5	M (6)	--	--	--	--	M (6)
2-1-3	--	L2 (4)	--	--	H2 (8)	--
5-1-3	--	L2 (2)	--	--	H2 (4)	--
2-6-3	--	H2 (4)	--	--	L2 (2)	--
5-6-3	--	H2 (8)	--	--	L2 (4)	--
2-1-4	--	H2 (4)	--	--	L2 (2)	--
5-1-4	--	H2 (8)	--	--	L2 (4)	--
2-6-4	--	L2 (4)	--	--	H2 (8)	--
5-6-4	--	L2 (2)	--	--	H2 (4)	--

Version 3

Previous Target Locations	Next Target Location					
	1	2	3	4	5	6
3-2-1	--	--	M (6)	M (6)	--	--
4-2-1	--	--	M (3)	M (3)	--	--
3-5-1	--	--	M (3)	M (3)	--	--
4-5-1	--	--	M (6)	M (6)	--	--
3-2-6	--	--	M (3)	M (3)	--	--
4-2-6	--	--	M (6)	M (6)	--	--
3-5-6	--	--	M (6)	M (6)	--	--
4-5-6	--	--	M (3)	M (3)	--	--
1-3-2	H2 (4)	--	--	--	--	L2 (2)
6-3-2	H2 (8)	--	--	--	--	L2 (4)
1-4-2	L2 (4)	--	--	--	--	H2 (8)
6-4-2	L2 (2)	--	--	--	--	H2 (4)
1-3-5	L2 (4)	--	--	--	--	H2 (8)
6-3-5	L2 (2)	--	--	--	--	H2 (4)
1-4-5	H2 (4)	--	--	--	--	L2 (2)
6-4-5	H2 (8)	--	--	--	--	L2 (4)
2-1-3	--	L1 (3)	--	--	H1 (6)	--
5-1-3	--	L1 (3)	--	--	H1 (6)	--
2-6-3	--	H1 (6)	--	--	L1 (3)	--
5-6-3	--	H1 (6)	--	--	L1 (3)	--
2-1-4	--	H1 (6)	--	--	L1 (3)	--
5-1-4	--	H1 (6)	--	--	L1 (3)	--
2-6-4	--	L1 (3)	--	--	H1 (6)	--
5-6-4	--	L1 (3)	--	--	H1 (6)	--

Version 4

Previous Target Locations	Next Target Location					
	1	2	3	4	5	6
3-2-1	--	--	M (3)	M (3)	--	--
4-2-1	--	--	M (6)	M (6)	--	--
3-5-1	--	--	M (6)	M (6)	--	--
4-5-1	--	--	M (3)	M (3)	--	--
3-2-6	--	--	M (6)	M (6)	--	--
4-2-6	--	--	M (3)	M (3)	--	--
3-5-6	--	--	M (3)	M (3)	--	--
4-5-6	--	--	M (6)	M (6)	--	--
1-3-2	L2 (4)	--	--	--	--	H2 (8)
6-3-2	L2 (2)	--	--	--	--	H2 (4)
1-4-2	H2 (4)	--	--	--	--	L2 (2)
6-4-2	H2 (8)	--	--	--	--	L2 (4)
1-3-5	H2 (4)	--	--	--	--	L2 (2)
6-3-5	H2 (8)	--	--	--	--	L2 (4)
1-4-5	L2 (4)	--	--	--	--	H2 (8)
6-4-5	L2 (2)	--	--	--	--	H2 (4)
2-1-3	--	H1 (6)	--	--	L1 (3)	--
5-1-3	--	H1 (6)	--	--	L1 (3)	--
2-6-3	--	L1 (3)	--	--	H1 (6)	--
5-6-3	--	L1 (3)	--	--	H1 (6)	--
2-1-4	--	L1 (3)	--	--	H1 (6)	--
5-1-4	--	L1 (3)	--	--	H1 (6)	--
2-6-4	--	H1 (6)	--	--	L1 (3)	--
5-6-4	--	H1 (6)	--	--	L1 (3)	--

Version 5

Previous Target Locations	Next Target Location					
	1	2	3	4	5	6
3-2-1	--	--	H2 (4)	L2 (2)	--	--
4-2-1	--	--	H2 (8)	L2 (4)	--	--
3-5-1	--	--	L2 (4)	H2 (8)	--	--
4-5-1	--	--	L2 (2)	H2 (4)	--	--
3-2-6	--	--	L2 (4)	H2 (8)	--	--
4-2-6	--	--	L2 (2)	H2 (4)	--	--
3-5-6	--	--	H2 (4)	L2 (2)	--	--
4-5-6	--	--	H2 (8)	L2 (4)	--	--
1-3-2	L1 (3)	--	--	--	--	H1 (6)
6-3-2	L1 (3)	--	--	--	--	H1 (6)
1-4-2	H1 (6)	--	--	--	--	L1 (3)
6-4-2	H1 (6)	--	--	--	--	L1 (3)
1-3-5	H1 (6)	--	--	--	--	L1 (3)
6-3-5	H1 (6)	--	--	--	--	L1 (3)
1-4-5	L1 (3)	--	--	--	--	H1 (6)
6-4-5	L1 (3)	--	--	--	--	H1 (6)
2-1-3	--	M (6)	--	--	M (6)	--
5-1-3	--	M (3)	--	--	M (3)	--
2-6-3	--	M (3)	--	--	M (3)	--
5-6-3	--	M (6)	--	--	M (6)	--
2-1-4	--	M (3)	--	--	M (3)	--
5-1-4	--	M (6)	--	--	M (6)	--
2-6-4	--	M (6)	--	--	M (6)	--
5-6-4	--	M (3)	--	--	M (3)	--

Version 6

Previous Target Locations	Next Target Location					
	1	2	3	4	5	6
3-2-1	--	--	L2 (4)	H2 (8)	--	--
4-2-1	--	--	L2 (2)	H2 (4)	--	--
3-5-1	--	--	H2 (4)	L2 (2)	--	--
4-5-1	--	--	H2 (8)	L2 (4)	--	--
3-2-6	--	--	H2 (4)	L2 (2)	--	--
4-2-6	--	--	H2 (8)	L2 (4)	--	--
3-5-6	--	--	L2 (4)	H2 (8)	--	--
4-5-6	--	--	L2 (2)	H2 (4)	--	--
1-3-2	H1 (6)	--	--	--	--	L1 (3)
6-3-2	H1 (6)	--	--	--	--	L1 (3)
1-4-2	L1 (3)	--	--	--	--	H1 (6)
6-4-2	L1 (3)	--	--	--	--	H1 (6)
1-3-5	L1 (3)	--	--	--	--	H1 (6)
6-3-5	L1 (3)	--	--	--	--	H1 (6)
1-4-5	H1 (6)	--	--	--	--	L1 (3)
6-4-5	H1 (6)	--	--	--	--	L1 (3)
2-1-3	--	M (3)	--	--	M (3)	--
5-1-3	--	M (6)	--	--	M (6)	--
2-6-3	--	M (6)	--	--	M (6)	--
5-6-3	--	M (3)	--	--	M (3)	--
2-1-4	--	M (6)	--	--	M (6)	--
5-1-4	--	M (3)	--	--	M (3)	--
2-6-4	--	M (3)	--	--	M (3)	--
5-6-4	--	M (6)	--	--	M (6)	--

APPENDIX D

The Awareness Questionnaire of Experiment 4

```
                3                              1
2 ---> 1 --->                  3 ---> 5 --->
                4                              6



                3                              1
5 ---> 1 --->                  4 ---> 5 --->
                4                              6



                3                              2
2 ---> 6 --->                  1 ---> 3 --->
                4                              5



                3                              2
5 ---> 6 --->                  6 ---> 3 --->
                4                              5



                1                              2
3 ---> 2 --->                  1 ---> 4 --->
                6                              5



                1                              2
4 ---> 2 --->                  6 ---> 4 --->
                6                              5
```

FOOTNOTES

1. An nth-order transition probability, $P(E|A_n- \ldots -A_2-A_1)$, is the probability of an event, E, occurring on trial t given the occurrence of events $A_n, \ldots, A_2, A_1$ on trials t - n, $\ldots$, t - 2, t - 1, respectively, and is defined as the number of times that E follows the run $A_n- \ldots -A_2-A_1$ divided by the total number of times that $A_n- \ldots -A_2-A_1$ occurs.

2. A lag n probability, $P(E|A-x-\ldots-x)$ where there are n - 1 x's, is the probability of an event, E, occurring on trial t given the occurrence of event A on trial t - n, and is defined as the number of times that E occurs n trials ahead of A divided by the total number of times that A occurs.

3. The reaction time difference between EE and EU runs was not significant, $p = .715$. One would have expected shorter reaction times on EE runs (e.g., 1-3-2-1-3), where the last element (e.g., 3) is primed, than on EU runs (e.g., 1-4-2-1-3), where the last element (e.g., 3) is not what is primed (e.g., 4). The absence of a difference was probably due to inhibition of recent elements (e.g., see Anastasopoulou & Harvey, 1999; Maylor & Hockey, 1985; Posner & Cohen, 1984; Rafal et al., 1989; also see Boyer, Destrebecqz, & Cleeremans, 1998). Primed elements occurred earlier in the runs causing priming to be offset by earlier inhibition. Inhibition of recent elements in the present experiment is evidenced by longer reaction times on UE runs (e.g., 6-3-2-1-3), where the last element occurs earlier in the run, than on UU runs (e.g., 6-4-2-1-3), where the last element does not occur earlier in the run, $p = .022$. To control for inhibitory effects and observe priming, reaction times on EE runs must be compared to those on UE runs, where in both cases, the last element occurs earlier in the run, and reaction times on EU runs must be compared to those on UU runs, where in both cases, the last element does not occur

earlier in the run.

4. To determine if learning of first-order probabilities was possible with much more narrowly separated target locations, the Present condition was replicated with the width of the display reduced from 14.1 cm to 4.0 cm. The replication also used different location markers. The bigram xo was replaced by two vertical lines, each 0.45 cm in height and 0.05 cm in width with the two lines separated by 0.15 cm. The left line had a 0.05 cm gap halfway up. For the bigram ox, only the right line had a 0.05 cm gap. Adjacent pairs of vertical lines were separated by 0.5 cm. Thus the entire width of the display was only 4.0 cm.

The results with the narrow display replicated those with the wider display. The effect of transition was significant, $p = .027$, as was the Transition x Session-L interaction, $p = .019$, reflecting the shorter reaction times on H than L transitions and an increasing difference across sessions (from 15 ms in session 1 to 35 ms in session 3). Thus there was learning of the first-order probabilities. The First x Last interaction was significant, $p = .007$, reflecting the shorter reaction times on EE than UE runs and longer reaction times on EU than UU runs. Thus priming effects were present. Finally, performance on the awareness questionnaire (45.83% correct) did not differ significantly from what would be expected by random guessing on the questionnaire (50% correct), $p = .551$. Thus there was no evidence for awareness of the first-order probabilities.

5. Further evidence for impaired performance in the Inconsistent group relative to the Consistent group comes from examining reaction times in the first and second blocks of the Present condition after switching from the Absent condition. Combining the data from sessions 2 and 3 to obtain a sufficient number of observations, the median reaction

time of correct responses in the Present condition was determined as a function of transition (L, H), set (1, 2), run completed (EE, UE, EU, UU), and block after a switch (first, second) for each participant. The reaction time difference between L and H transitions was significantly greater in the Consistent than Inconsistent group in the first block after a switch (35 ms versus 15 ms), $p = .018$, but not in the second block (33 ms versus 23 ms), $p = .249$. In the Inconsistent group, the reaction time difference between L and H transitions was not significant in the first block after a switch, $p = .067$ (one-tailed), but was significant in the second block, $p = .022$ (one-tailed). Thus impairment in the Inconsistent group appeared to be limited to the first block after switching from the Absent condition.

6. Error rates in the four experiments were also examined. Most results did not approach significance ($ps > .10$). The few results that were significant or approached significance generally reflected a pattern of error rates that paralleled the pattern of reaction times (e.g., a higher error rate on L than H transitions or a larger error rate difference between L and H transitions in the Present than Absent condition). Thus there was no evidence that the reaction time differences between L and H transitions and between runs were due to speed-accuracy tradeoffs.

7. One explanation is that with the narrowly separated target locations in the Present condition, the gaps in a display created by the letter C (e.g., O O C O C C) may have been particularly salient. Consequently, when the ordering of the letters was changed immediately after a response, the movement of the gaps may have functioned as an abrupt visual change that automatically captured visuospatial attention (e.g., see Folk et al., 1994; Jonides, 1981; Jonides & Yantis, 1988; McCormick, 1997; Muller & Rabbitt,

1989; Remington et al., 1992). The capture of attention may have prevented the processing of information at an anticipated target location, thereby eliminating the Present condition's sensitivity to learning of the first-order probabilities and to priming effects. Alternatively, the capture of attention may have hindered learning or priming by effectively creating a new, more complex sequence of target locations (or attentional shifts) where every second element was random.

Consistent with the capture of attention hypothesis, the experiment outlined in footnote 4 used a similar sized display but without highly salient features. In that experiment, robust first-order probability learning and priming were observed. Although the pilot and footnote experiments were not designed to study the effects of abrupt visual distractors on pure perceptual-based learning, they do suggest that such studies might elucidate the relationship between pure perceptual-based learning and visuospatial attention.