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Sequences learned without awareness can orient attention during the perception of human activity

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Human activity contains sequential dependencies that observers may use to structure a task environment (e.g., the ordering of steps when tying shoes or getting into a car). Two experiments investigated how people take advantage of sequential structure to understand activity and respond to behaviorally relevant events. Participants monitored animations of simplified human movement to identify target hand gestures. In the first experiment, participants were able to use predictive sequential dependencies to more quickly identify targets. In addition, performance was best at the point in time that followed the sequence. However, the second experiment revealed that how sequential structure affects detection depends on whether the sequence predicts the timing of target events. In all cases, sequence learning was observed without participants' awareness of the sequential dependencies. These results suggest that human activity sequences can be learned without awareness and can be used to adaptively guide behavior.

Perceiving human activity relies on a variety of cues including distinctive visuospatial and auditory patterns, knowledge about actors' goals, and culturally determined "scripts." Here we focus on perceivers' use of sequential structure in activity—the fact that strings of actions often predictably follow one another. Sequential structure may be particularly helpful for orienting attention to informative moments in time. Suppose you are at a large family gathering and your new in-law decides to make peanut butter sandwiches for everyone. While chatting with him, you may incidentally learn the sequence of steps he takes to make the sandwiches. Now suppose you get hungry and would like the next sandwich your in-law makes with strawberry jelly. (He's making some with strawberry and some with grape.) Since you know when your in-law is likely to grab a jar of jelly, you know when to look to see if it's strawberry or grape. Thus, a cue to *when* an important behavior is likely to occur (when a jar will be grabbed) can guide behavior even if it doesn't predict other task-relevant features of behavior (whether the jar contains grape or strawberry jelly). Previous research has shown that observers can learn sequential structure in responses, phonemes, visual shapes, and even cognitive tasks (e.g., Fiser & Aslin, 2002; Gotler, Meiran, & Tzelgov, 2003; Nissen & Bullemer, 1987; Saffran, Newport, & Aslin, 1996; Seger, 1994). Given that people can learn sequential structure, it makes sense to ask how they use it to better perform tasks.

Sequential structure may influence task performance in at least three ways. First, the end of a sequence may indicate that the stimulus stream is about to become unpredictable and requires additional processing (Brown & Braver, 2005; Yu & Dayan, 2005). Second, sequential structure may allow one to predict when one would best be able to detect an event *if* it occurs. Third, sequential structure may predict when an important event is likely to occur, without indicating what that event will be. In the second and third cases, people may use the sequence as a cue to orient attention to a particular moment. Individuals have the ability to direct attention to particular points in time that are explicitly cued by simple visual stimuli (Nobre, 2001). Similarly, sequences of visual events may act as contextual cues for the onset of targets. This was demonstrated in several experiments in which participants viewed a series of 15 briefly presented simple visual stimuli (e.g., letters) and responded whenever a target appeared (Olson & Chun, 2001). In an initial learning phase, the target was always preceded by one of eight fixed sequences, three to ten items long. Performance improved throughout training, but when these sequences were later removed performance became reliably worse.

It is difficult to generalize previous findings to situations where observers may use features of another person's activity to determine when to act. First, there is extensive evidence for specialized mechanisms for perceiving human action (Parsons, 1987; Shiffrar & Freyd, 1990), so data from research based on simple visual shapes or sounds may not generalize well to the domain of human action. Second, studies of cuing attention in time have used brief, well-defined trials, whereas human activity is extended in time (e.g, Nobre, 2001; Olson & Chun, 2001). Third, experiments that have used extended visual streams conflated attentional cuing with learning the perceptual and motor features of a sequence. In serial response time

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tasks (Nissen & Bullemer, 1987; Seger, 1994), performance is helped more by learning the relations between sequences of visual features and sequences of actions than it is by learning when to respond. Sequence discrimination (Fiser & Aslin, 2002) and infant habituation paradigms (Kirkham, Slemmer, & Johnson, 2002) employ offline recognition or habituation tests (but see Turk-Browne, Jungé, & Scholl, 2005). These experiments test memory for what the sequence was rather than assessing the effects of the sequence on viewers' attention over time. Thus, an important question remains: Can people learn and use sequential structure in extended human movement patterns to guide performance if the sequence indicates when a target will appear but not what the target is?

To ask if and how people use sequential structure in activity to guide perception and action, we conducted two experiments in which participants looked for target hand gestures in extended streams of pictures depicting simple simulated human movement.

EXPERIMENT 1

The first experiment was designed to determine whether people can learn a recurring sequence in human activity, when that sequence predicts *when* an important stimulus will appear, but not *where* it will appear or *what* it will be. Participants were shown a continuous stream of pictures depicting a man with his arm in different positions and his hand forming different gestures (Figure 1). Two of these gestures were targets to which the participants made a manual response. A sequence of seven arm positions was repeated within the stream of otherwise randomly selected stimuli. For the first three-quarters of the task, target gestures appeared immediately after the sequence. We compared performance on this part of the task to performance on the last quarter of the task, during which the sequence was present but was unrelated to the onset of the target.

Method

Participants. Eight participants (3 female, 19–22 years old) were recruited from Washington University, and received credit toward course requirements for participating. An additional participant left before the end of the study.

Target detection. The stimuli and design of this task are illustrated in Figure 1. Seventy-eight pictures (*frames*) depicting a man with his right arm in six positions and forming 13 hand gestures were created using graphic design software (Poser 5, e frontier, Inc., Scotts Valley, CA) and presented with a Macintosh G3 computer on a 19-in. monitor. Stimuli were presented using PsyScope experimental software (Cohen, MacWhinney, Flatt, & Provost, 1993).

Participants monitored a stream of 4,480 serially presented frames (approximately 15.5º square) for two target gestures and were instructed to press the appropriate button on a button box whenever either target gesture appeared. Responses were immediately followed by a beep if correct or a buzz if incorrect. If no response was made within 2.25 sec, the computer buzzed. To induce long-range apparent motion, frames appeared at the center of the screen for 750 msec with no interstimulus interval. Embedded within the stream were 320 repetitions of a single sequence of seven arm posi-

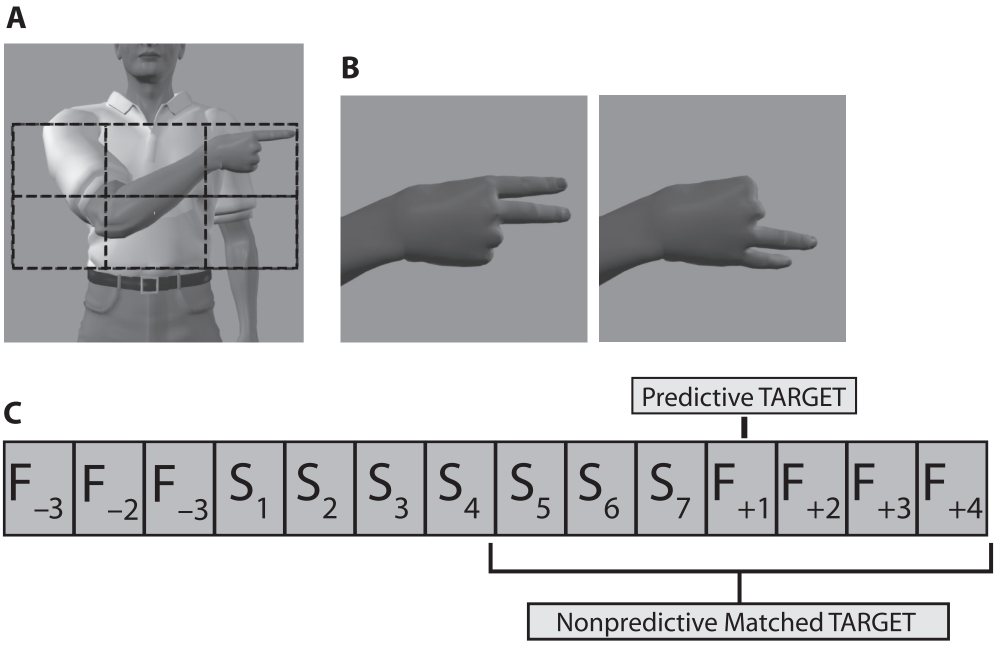

Figure 1. Target detection task and stimuli used in Experiment 1. (A) The stimuli (frames) depicted a man posed with his hand in any of six locations (dashed line added for illustrative purposes). The man's right hand formed 13 different gestures in which each finger other than the thumb either extended or bent behind the palm. During the target detection task, participants pressed the appropriate button whenever one of two target gestures (B) appeared. Trials (e.g., panel C) consisted of the sequence of arm positions (S_1 to S_7) surrounded by seven randomly generated arm positions (F_{-3} to F_{+4}) paired with randomly selected nontarget gestures. During predictive trials, the sequence of arm positions was immediately followed by a target gesture. During nonpredictive matched trials, the target appeared within the range of possible target locations in predictive trials.

tions, randomly generated for each participant. Although they were not apparent to participants, the stimulus stream was divided into trials of 14 frames. Each trial began with one to six random arm positions (*fillers*), followed by the seven frame sequence, followed by the target gesture (appearing with a random arm position), and concluding with zero to five fillers. All gestures other than the target were randomly determined. Immediate repetition of gestures and arm positions was prevented (Figure 1).

During the first three-quarters of the experiment, the sequence of arm positions was immediately followed by one of the target gestures (*predictive trials*). Because the arm position that ended the sequence also appeared as a filler position, this arm position was not fully predictive of the target on its own (mean conditional probability of the target following the same arm position = .387, *SD* = .078). During the last quarter of the task, target appearance was randomly determined, with the distribution of intertarget intervals matched to that of predictive trials (*nonpredictive matched trials*). This ensured that the intervals between targets in the last quarter of the task matched those in the predictive trials and removed the perfect sequential relationship between the repeating sequence and the target.[1]

Participants performed sets of 20 practice trials, without the sequence, until they correctly detected at least 80% of the targets. One person needed two sets; all others needed one set.

Questionnaires and cued generation recall. Participants completed a questionnaire designed to assess awareness of the sequence by asking several open-ended questions about whether the participant noticed anything unusual about the task, the sequence of stimuli, or if they noticed any repeating sequences of arm position. They also completed a cued generation recall test (Figure 2). The test began with a screen displaying the first item in the sequence and the six possible arm positions. Participants were instructed to indicate the next item in the sequence by pressing the letter on the keyboard that appeared below their selection. They were then shown the correct position. This process was repeated for the remaining five items in the sequence. Participants then were asked whether they remembered seeing the sequence during the target detection task.

Procedure. After the participant provided informed consent, the experimenter described the target detection task and began the practice trials. The experimenter told the participant that the task would periodically pause for breaks and left the room. During breaks average response time and accuracy for the last 40 trials were displayed and the participant was encouraged to improve. Following the target detection task, the participant responded to questions designed to assess awareness of the repeating sequence. The experimenter then told the participant about the repeating sequence and administered the cued generation recall task aloud. Finally, the experimenter asked the participant if he or she remembered any regularities in when the target gesture occurred.

Results and Discussion

Each participant's distribution of target detection response times was trimmed to remove responses faster than 200 msec or slower than three *SD* above the mean. To correct for preexisting differences in speed across participants, individual response time distributions were transformed using the mean and the standard deviation of their last 20 practice trial response times. These transformed scores were averaged within *epochs* of 20 trials. Means and standard errors for each epoch are depicted in Figure 3A.

As participants progressed through the predictive epochs of the task their response times steadily decreased [mean correlation = $-.676$, *SD* = .22; $F(1,7) = 16.247$, $p = .005$, $\eta_p^2 = .699$]. However, response times increased after the task transitioned to nonpredictive matched trials. The difference between response times during the last four predictive epochs and the nonpredictive matched epochs was significant [$t(7) = -4.714$, $p = .002$, $d = -1.667$] and occurred without a reliable change in error rates across epochs [$F(15,105) = 0.571$, $p = .89$, $\eta_p^2 = .075$].

If sequences benefit performance only when the target immediately follows them, then targets should be more quickly detected when they immediately follow the sequence than when they appear in surrounding frames. To test this hypothesis we performed an additional analysis on the nonpredictive matched trials (Figure 3B). For this analysis, performance was evaluated for targets that appeared at different temporal locations around the end of the sequence.[2] The speed with which targets were detected varied with the temporal location of the target [$F(5,35) = 2.592$, $p = .0423$, $\eta_p^2 = .27$], without a reliable change in error rates [$F(5,35) = 1.544$, $p = .2$, $\eta_p^2 = .181$]. In particular, targets that appeared in the first frame following the sequence were detected faster than targets that appeared at the end of the sequence [$t(7) = -4.966$, $p = .002$, $d = -1.756$] and those that appeared in the second

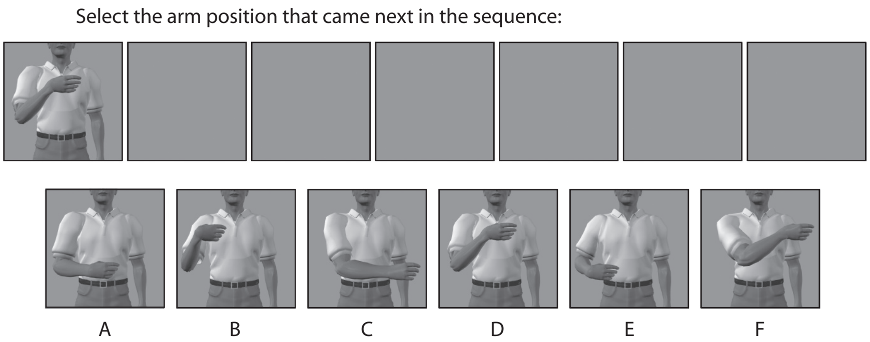

Figure 2. An example of the first trial of the cued generation recall task. The bottom row depicted the six possible arm positions (neutral gesture) in a random order. The top row displayed the first item in the sequence followed by six blank pictures. On each trial, the next item in the sequence was filled in. Participants selected the next item by pressing the letter under the picture of the arm position.

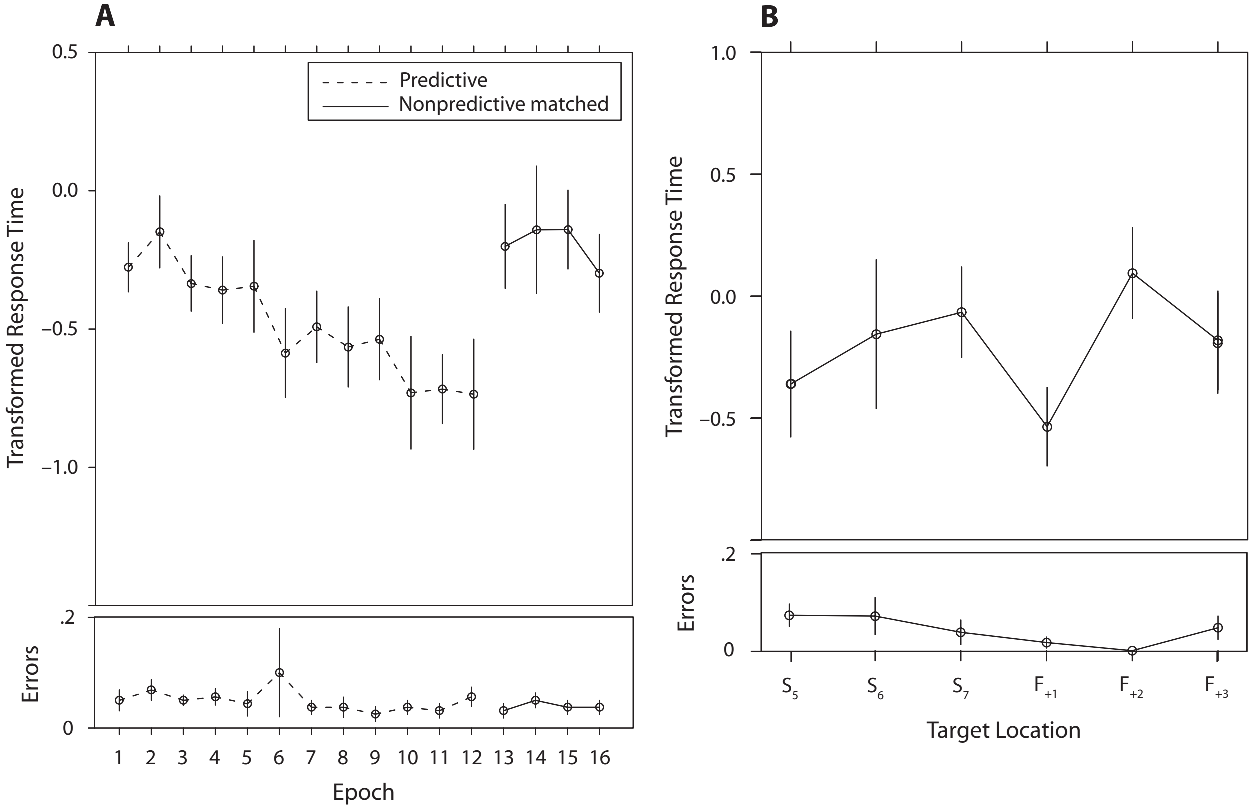

Figure 3. Performance on the target detection task in Experiment 1. (A) Transformed response time and error rate (percentage of missed targets and incorrect responses) for each epoch of 20 trials. (B) Transformed response time and error rate during the last four nonpredictive matched epochs, as a function of the target's temporal location around the end of the sequence (location S_7). Trials with targets occurring during the sequence (S_5 to S_7) or following it (F_{+1} to F_{+3}) were analyzed. All error bars are standard errors of the means.

frame following the sequence [$t(7) = -2.949$, $p = .02$, $d = -1.043$].

Although participants benefited from the sequence, they were unaware of its presence. None of the participants explicitly mentioned the sequence when responding to the questionnaires, nor did they perform above chance levels on the cued generation task.[3] However, two participants did describe square or circular movement patterns.

In sum, participants detected targets faster when targets followed the recurring sequence of arm positions, though they failed to report the existence of the sequence and were unable to reproduce it.

EXPERIMENT 2

The results of Experiment 1 support the hypothesis that people can, without awareness, learn a repeating action sequence and use it to guide task performance *(learned attention guidance*). This extends Olson and Chun's (2001) findings to long streams of simulated human activity. However, *prediction-based attentional control* theories (Brown & Braver, 2005; Yu & Dayan, 2005) posit a mechanism that orients attention or increases control when activity becomes unpredictable, independent of whether anything important is likely to happen at that moment. On this view, responses on frames after the repeating sequence in Experiment 1 were faster because hand location became less predictable on those frames, not because participants had learned that targets were likely to appear then.

Experiment 2 pitted the learned attention guidance account against the predictability-based attentional control account by manipulating the relationship between the end of the sequence and target onset: Some participants were trained with repeating sequences that were always followed by a target gesture, and other participants were trained with repeating sequences that never predicted when the target would appear. If the predictability-based attentional control account of Experiment 1 were correct, both groups should be fastest on the frame following the repeating sequence, when spatial predictability drops. If the learned attention guidance account were correct, only the group for whom the target gesture always followed the sequence should show this effect.

Method

Participants. Sixty-three participants (43 female, 18–25 years old) were recruited from Washington University, and received course credit or $15 for participating. Data from an additional 7 participants were excluded because of poor performance.[4]

Target detection. Three modifications were made to the target detection task of Experiment 1. First, predictiveness was manipulated between rather than within participants; for some participants, the sequence never predicted when the target would appear. Second, in Experiment 1 the targets in the nonpredictive matched trials occurred near the end of the trials to preserve the spacing of target appearances, resulting in a weak relationship between the sequence and target. To remove this relationship, a *nonpredictive unmatched* group was added. For this group, targets could appear at any point in the trial. There were 20 participants each in the predictive and nonpredictive matched groups, and 23 in the nonpredictive unmatched group. Third, the length of the task was reduced from 4,480 to 2,800 frames. Participants practiced the task until they correctly detected at least 80% of the target gestures. (Four participants required two sets of practice trials.)

Questionnaires and cued generation recall. The questionnaire procedure and cued generation recall test were the same as in Experiment 1.

Procedure. The procedure was nearly identical to that of Experiment 1. However, between the target detection and cued generation recall tasks, participants were exposed to 40 more sequence presentations in an event segmentation task (Newtson, 1973). Data from this task will not be reported here.

Results and Discussion

Transformed response times and accuracy for the target detection task are depicted in Figure 4A. Response times improved as the task progressed [$F(9{,}540) = 27.572$, $p < .001$, $\eta_p^2 = .315$]. The predictive group was faster than the two nonpredictive groups [$F(2{,}60) = 7.338$, $p = .002$, $\eta_p^2 = .197$], and response times decreased differently across groups [$F(18{,}540) = 1.802$, $p = .022$, $\eta_p^2 = .057$]. A focused contrast on the slopes of regression lines fit to each individual's data revealed that response times decreased more rapidly when the sequence was predictive than when it was nonpredictive [$F(1{,}61) = 5.755$, $p = .02$, $\eta_p^2 = .086$]. Accuracy improved slightly with practice, with errors decreasing from .068 in Epoch 1 to .052 in Epoch 10 [for epoch, $F(9{,}540) = 5.401$, $p < .001$, $\eta_p^2 = .083$; for group, $F(2{,}60) = 0.314$, $p = .732$, $\eta_p^2 = .01$; for the interaction, $F(18{,}540) = 0.6947$, $p = .818$, $\eta_p^2 = .023$]. In short, participants became faster with practice, especially those in the predictive group. This replicates the main finding of Experiment 1 in a between-participants design.

Because the spatial location of the gesture became unpredictable after the sequence, the attentional control account makes the specific prediction that responses should be fastest on frames that immediately follow the repeating sequence. To test this hypothesis, nonpredictive matched and nonpredictive unmatched group performance was analyzed as a function of the target's temporal location.[5] (This analysis was not performed for the predictive group, for whom the targets always appeared at the same temporal location.) As can be seen in Figure 4B, responses were not fastest on the frame immediately following the sequence. This militates against the predictability-based attentional control account.

However, target detection was faster at some temporal locations than at others [for target location, $F(7{,}287) =$

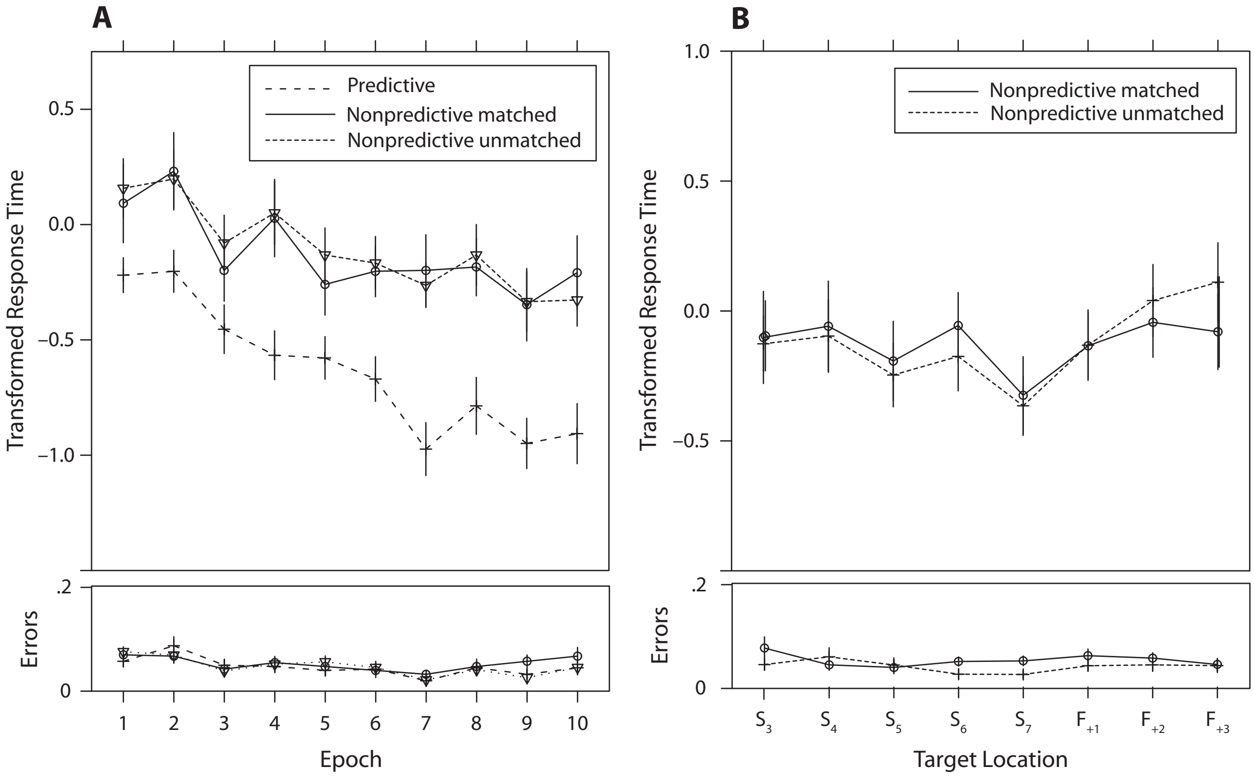

Figure 4. Performance on the target detection task in Experiment 2. (A) Transformed response time and error rates (percentage of missed targets and incorrect responses) for each group are illustrated for epochs of 20 trials. (B) Transformed response time and error rates for the two nonpredictive groups as a function of target's temporal location. Trials with targets occurring during the sequence (S_3 to S_7) or following it (F_{+1} to F_{+3}) were analyzed. Error bars are standard errors of the means.

4.443, $p < .001$, $\eta_p^2 = .098$; for group, $F(1,41) < 1$, $p = .99$, $\eta_p^2 < .001$; for the interaction, $F(7,287) = 0.724$, $p = .652$, $\eta_p^2 = .017$]. In the nonpredictive conditions of Experiment 2, unlike the predictive condition of Experiment 1, detection was faster on the last frame of the sequence than on the following frame [$t(42) = 2.869$, $p = .006$, $d = 0.438$]. This effect is consistent with the learned attention guidance account: If focusing attention at one point in time reduces one's ability to focus at other points (Chun & Potter, 1995), it would be adaptive to focus attention on those points that best support task performance. In the nonpredictive conditions it would be best to attend when the position of the gesture is most certain and provides the best opportunity to ascertain if it is a target gesture.

This effect was specific to the sequence. We categorized targets according to whether they occurred with the last arm position in the sequence, an arm position that was the same as the last arm position in the sequence, or with arm positions that were different than the last arm position in the sequence (Figure 5). For both groups, response times to targets that appeared at the end of the sequence were fastest, leading to a main effect of arm position type [$F(2,82) = 10.952$, $p < .001$, $\eta_p^2 = .211$; for group, $F(1,41) = 0.015$, $p = .904$, $\eta_p^2 < .001$; for the interaction, $F(2,82) = 0.21$, $p = .811$, $\eta_p^2 = .005$]. Response times to targets that occurred at the end of the sequence were significantly faster than those to targets that occurred on the same arm position outside of the sequence [$t(42) = -2.768$, $p = .008$, $d = -0.422$]. Error rates were not significantly affected by the temporal location of the target [for target location, $F(7,287) = 0.913$, $p = .497$, $\eta_p^2 = .022$; for group, $F(1,41) = 1.942$, $p = .171$, $\eta_p^2 = .045$; for the interaction, $F(7,287) = 1.024$, $p = .414$, $\eta_p^2 = .024$].

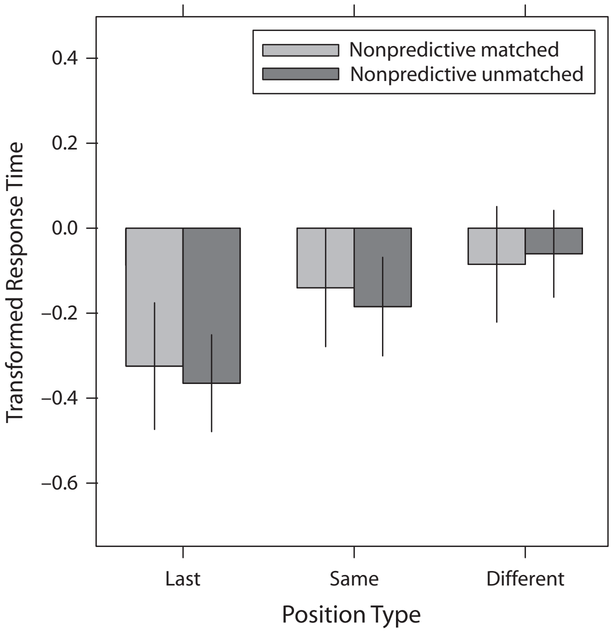

Figure 5. Performance as a function of arm position type in Experiment 2. Transformed response times for trials when the target occurred with an arm position that was the last position in the sequence, the same as the last position in the sequence (but not occurring at the end of the sequence), or a different position. Error bars are standard errors of the means.

In this experiment, 21 of the participants described short linear movements, 3 described motion in terms of simple actions, 5 described short two- to three-item sequences, and 3 described a sequence longer than four items in response to the questionnaire. Nine participants demonstrated awareness of the sequence in the cued generation recall task (*predictive* = 1; *nonpredictive matched* = 3; *nonpredictive unmatched* = 5). This increase in awareness was probably due to the segmentation task performed between the target detection task and cued generation recall, which asked participants to attend to the pictured person's activity. Removing participants that demonstrated awareness of the sequence did not substantively alter the results of the analyses.

GENERAL DISCUSSION

Using extended stimulus streams, these experiments demonstrated that observers were able to learn sequences of locations in simulated human activity to better respond to another feature of the same activity. Activity sequences were learned both when they did and did not predict when a target event would occur. However, the predictive relationship between the activity sequence and target onset influenced how observers used the sequence to guide task performance. Despite the benefit of the sequence to task performance, most participants were unable to demonstrate awareness of the sequence in a cued generation recall task.

Together, these two experiments provide insight into the three ways sequential structure may guide attention and action. First, sequential structure may guide activity by producing transient increases in attentional control when sequential dependencies become low and perceptual information becomes unpredictable (Sokolov, Nezlina, Polyanskii, & Evtikhin, 2002; Yu & Dayan, 2005). If this were the case, performance should have been best on the frame following the arm position sequence in both Experiments 1 and 2. However, in Experiment 2 participants in the nonpredictive conditions were fastest when targets occurred on the final frame, but not after.[6]

Sequential structure may also allow one to learn when events of interest are likely to occur (Olson & Chun, 2001). The data provided strong support for this type of learning. In Experiment 1, after repeated training that a target hand gesture always followed the end of a sequence of arm positions, participants were fastest when targets occurred at this point in time and slower when targets occurred at times that violated this expectation.

Even when sequential structure does not predict when an event will occur, it may predict when the event is most easily detected *if* it occurs. Experiment 2 provided evidence for this type of learning. In the nonpredictive conditions the sequence did not allow participants to predict *when* a target would occur or *what* it would be, but did allow them to predict, for some frames, *where* the target would be if it did occur.

The perception of goal-directed activity relies on the dynamic interplay of systems involved in the recognition of biological motion patterns, goals, and intentions (Zacks, Speer, Swallow, Braver, & Reynolds, 2007). In addition to being informative in their own right, these aspects of activity produce sequential dependencies in behavior. The present data show that sequential dependencies in human activity can be learned without recourse to constraints from biological motion, goals, or intentions, and without awareness or intent. Further, such learning influences how observers structure their task environment. The way sequences are used to structure performance appears to be flexible, so people can use sequential structure however is most adaptive in a particular situation.

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NOTES

1. During nonpredictive matched trials, targets appeared after the sequence an average of 12.125 times (*SD* = 3.44, range 8–19), after the arm position that was the same as the last position in the sequence an average of 6 times (*SD* = 4.037, range 2–13), and after all other arm positions an average of 61.875 times (*SD* = 6.244, range 53–70). The small number of targets that followed the same arm position did not afford reliable comparisons of performance across these conditions.

2. Only those target temporal locations for which nearly all participants had at least five data points were included in the analyses, resulting in the inclusion of frames S_5 to F_{+3}.

3. Chance performance was defined based on the .2 binomial probability of guessing correctly on each frame. A partial credit scoring method (arm positions adjacent to the correct position received partial credit) with a Monte Carlo–simulated probability distribution led to the same conclusion

4. Six participants were excluded based on accuracy [overall accuracy was more than two standard deviations below the mean accuracy (M = .942, SD = .042) or accuracy for a given epoch was more than three standard deviations below mean epoch accuracy (M = .942, SD = .073)]. One participant whose overall rate of learning was more than two standard deviations above the mean learning rate was also excluded (indexed by the b-weight of a linear equation describing response time across epochs, M = −6.56, SD = 6.44).

5. Only those target temporal locations for which nearly all participants had at least five data points were included in the analyses. As a result frames S_3 to F_{+3} were included in Experiment 2.

6. The observed benefits may have been due to response preparation rather than the allocation of attention per se. An analysis of false alarm rates provided no evidence to suggest that this was the case. However, false alarm rates were too low to draw reliable conclusions from this analysis.

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