Psychological Research
DOI 10.1007/s00426-014-0546-8

ORIGINAL ARTICLE

How does implicit learning of search regularities alter the manner in which you search?

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Received: 30 August 2013 / Accepted: 4 February 2014

Abstract Individuals are highly sensitive to statistical regularities in their visual environment, even when these patterns do not reach conscious awareness. Here, we examine whether oculomotor behavior is systematically altered when distractor/target configurations rarely repeat, but target location on an initial trial predicts the location of a target on the subsequent trial. The purpose of the current study was to explore whether this temporal-spatial contextual cueing in a conjunction search task influences both reaction time to the target and participant's search strategy. Participants searched for a target through a gaze-contingent window in a display consisting of a large number of distractors, providing a target-present/absent response. Participants were faster to respond to the target on the predicted trial relative to the predictor trial in an implicit contextual cueing task but were no more likely to fixate first to the target quadrant on the predicted trial (Experiment 1). Furthermore, implicit learning was interrupted when instructing participants to vary their searching strategy across trials to eliminate visual scan similarity (Experiment 2). In Experiment 3, when participants were explicitly informed that a pattern was present at the start of the experiment, explicit learning was observed in both reaction time and eye movements. The present experiments provide evidence that implicit learning of sequential regularities regarding target locations is not based on learning more efficient scan paths, but is due to some other mechanism.

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Introduction

Despite the enormous complexity of the visual environment, individuals are quite adept at goal-directed visual search, due in part to our sensitivity to statistical regularities (whether they are explicit or implicit). For instance, when entering a friend's house and searching for a coffee pot, we know the most probable location for the item is in the kitchen. Furthermore, when we arrive in the kitchen, we tend to first examine locations where we believe the coffee pot is likely to be, such as the countertop, relative to locations where it is unlikely to be, such as the kitchen floor or in the refrigerator. Similarly, implicit knowledge can also influence search. For instance, in searching the kitchen for the coffee pot we may prioritize locations that remind us of where the coffee pot is in our own kitchen in the absence of any sort of conscious awareness that attention has been biased in this manner. Individuals are therefore highly sensitive to the probability of a target appearing in a specific location as a result of our frequent exposure over time (Biederman, 1972). Unsurprisingly then, targets located in an expected location are detected faster relative to targets in an unlikely location (e.g., Fiser & Aslin, 2002; Saffran, 2002). When environmental probabilities are explicitly learned, it is quite clear how knowledge influences search. Specifically, participants would become more likely to direct their eye movements toward locations where the target is highly likely to appear, ignoring lower probability locations. Less clear, however, is the question of whether eye movement patterns are influenced when environmental probabilities are implicitly learned. Though individuals are faster to detect targets appearing in statistically likely locations, it is unknown whether this speeding is attributable to changes in oculomotor behavior or whether the reduction in reaction time is associated with other processes (e.g., response criterion). Therefore, the purpose of the current study was to examine whether eye movements are systematically altered when examining distractor/target search configurations, where a trial-pair contingency dictates that the target location on an initial trial always predicts the location of a target on the subsequent trial.

Given the role for both implicit and explicit knowledge in search behavior, it is no surprise that attentional deployment is influenced by both bottom-up and top-down factors. In terms of low-level influences, differences in target and distractor color (D'Zmura, 1991; Theeuwes, 1994, 1992), motion (Dick, Ulman, & Sagi, 1987; McLeod, Driver, & Crisp, 1988; Rosenholtz, 2001), orientation (Foster & Ward, 1991; Moraglia, 1989), and size (Carrasco, McLean, Katz, & Frieder, 1998) will typically result in attentional capture, and thus faster detection of the target amongst any number of distractors (see Wolfe & Horowitz, 2004, for a review). Furthermore, we are faster at responding to targets that appear in a familiar location over time relative to an unfamiliar one, known as *probability cueing* (see Druker & Anderson, 2010; Geng & Behrmann, 2005; Kabata & Matsumoto, 2012; Jiang, Swallow, & Rosenbaum, 2013). Knowledge-based factors play an equally important role in determining the manner in which we attend to a scene, where memory (Jiang, Swallow, Rosenbaum, & Herzig, 2013) and task instruction (Dodd, Van der Stigchel, & Hollingworth, 2009; Smith & Henderson, 2009) among other factors influence eye movement behavior and search strategy. Chun and Jiang (1998) further demonstrated the importance of *contextual cueing* in how we deploy attention, defined as how the visual context and global properties of an image guide visual search, where such knowledge is learned implicitly. In their study, participants completed a target detection task, where they had to search for the letter "T" among 11 distractors items (letter "L"), and then determine the orientation of the target letter. Critically, several search arrays were repeated across the experiment, such that the spatial context of distractors predicted target location in these displays. Although participants were never aware of these recurrences (limited number over 720 trials), participants displayed a reduction in RT for repeat relative to novel displays, demonstrating that participants were implicitly learning the context of displays which in turn assisted in target detection.

Previous research has also examined the manner in which eye movements are altered in terms of context-facilitated search. Utilizing a paradigm similar to that of Chun and Jiang (1998), Peterson and Kramer (2001) determined that during repeated search arrays, participants utilized not only fewer fixations, but were also more inclined to have their first fixation directly land on the target location, relative to when searching a novel display. Similarly, Tseng and Li (2004) had participants search for and judge the orientation of a "T" amongst a series of distractor "L"s, but included irrelevant blue disks in the search array which served as a contextual cue. Interestingly, although participants stated that they ignored the contextual cue and fixations never fell on the blue disk, participants had decreased search time and fewer saccades in repeat displays relative to novel displays. However, fixation duration, saccade amplitude, the time from last fixation, and response time did not differ between repeat and novel displays, demonstrating that the implicit learning taking place appears to manifest in fewer fixations. It appears then that the target in repeat trials is not necessarily "popping out" in a bottom-up sense, but over time an implicit contextual memory is developed that facilitates target detection.

The purpose of the current study is to further unravel the relationship between global statistical properties and implicit learning as it relates to eye movements. We utilize target-pair contingencies, where the location of the target on trial N predicts the quadrant in which the target appears on trial $N + 1$ (for a similar paradigm, see Stadler, 1989 and Ziessler, 1994 who utilized a visual search paradigm where target location on preceding trials predicted target location on a future trial). This is a departure from previous research examining statistical learning and contextual cueing, where normally participants implicitly learn the probable location of a target over trials through simple repetition of target location (i.e., Chun & Jiang, 1998). We are interested in whether these more indirect statistical regularities can facilitate visual search. Moreover, to fully examine the influence of these contingencies on implicit learning, we employ a gaze-contingent window to force serial processing of target/distractors in determining whether oculomotor behavior changes over time. Specifically—in addition to response time—we are interested in how quickly participants fixate the quadrant where the target appears when target location is predictable based on the previous target location. That is, as participants learn search regularities, are they faster and more likely to fixate the correct target quadrant or is oculomotor behavior unaffected? In previous contextual cueing studies, the use of rather small search arrays in which the entire display is present at the beginning of each trial leads to relatively fast reaction times and little time to determine how eye movements are modified by learning (indeed, eyetracking measures are generally used with regard to the probability that the first fixation lands on the target as opposed to search patterns per se). Moreover, in the present study, no visual information is presented at fixation to bias initial eye movements, and therefore we will be able to examine if only the contingency alters search. Collectively, the paradigm provides a more sensitive measure of the degree to which eye movements are influenced by implicit learning. Moreover, our stimuli are meaningless configurations (circles and squares that are either red or blue) so as to eliminate bias due to prior knowledge or expectations, enabling a clearer understanding of whether participants are implicitly establishing global contextual information over time.

Experiment 1

In Experiment 1, we examine whether oculomotor behavior is altered when images and distractor/target arrays rarely repeat, but target location on an initial trial predicts the location of a target on the subsequent trial in a target-pair contingency (e.g., a target in the lower left quadrant on trial *N* means the target will appear somewhere in the upper right quadrant on trial $N + 1$).

Method

Participants

Nineteen undergraduate students from the University of Nebraska-Lincoln participated in the study and received course credit for their participation. All participants had normal or corrected-to-normal vision and were naïve to the purpose of the study that took place in a single 60-min session.

Apparatus and procedure

The eye tracker was an SR Research Ltd. EyeLink II system (Mississauga, Ontario, Canada), with high spatial resolution and a sampling rate of 500 Hz. For all participants, the dominant eye was monitored. Thresholds for detecting the onset of a saccadic movement were acceleration of $8{,}000°/s^2$, velocity of 30°/s, and distance of 0.5° of visual angle. Movement offset was detected when velocity fell below 30°/s and remained at that level for ten consecutive samples. The average error in the computation of gaze position was <0.5°. A nine-point calibration procedure was performed at the beginning of the experiment, followed by a nine-point calibration accuracy test. Calibration was repeated if any point was in error by more than 1° or if the average error for all points was >0.5°. Participants completed the experiment on a Pentium IV PC seated approximately 44 cm from the computer screen and made responses using both eye movements and the controller in front of them. Further, participants searched for the target through a gaze-contingent window measuring $2° \times 2°$ visual degrees, such that participants could only see where they were fixating, with the remainder of the screen appearing black. All eye movement data were computed via individual interest areas assigned to each of the four quadrants of the experimental display.

For all participants, the experiment consisted of the presentation of 330 search displays divided evenly across three blocks. Each display contained 32 squares and circles measuring $1° \times 1°$ and an example of a search display can be found on Fig. 1. All displays have eight items in each quadrant but the displays were designed such that none of the stimuli could be viewed at fixation when the trial began. This means that the location of the first fixation was internally generated by the participant as none of the target and distractors items could be used to bias attention toward or away from a particular search quadrant. On no-target trials (without a red square), 16 of the squares were blue and 16 of the circles were red, divided evenly across the four quadrants. On target trials, one of the blue squares in one of the quadrants was replaced with a red square. Within a quadrant, the shapes varied in degree of proximity and in placement relative to one another, but no objects touched any other objects nor did any of the objects overlap the *x* or *y* axis. At the beginning of each trial, a fixation point appeared in the middle of the screen; participants were instructed to look directly at the fixation point and press the space bar to initiate each trial. Once the trial was initiated, the fixation point was removed and participants began searching through the gaze-contingent window. Participants were instructed to determine whether or not a red square (the target) was present during each trial and responded with a controller utilizing their right hand. Participants pressed one key for target present and another for target absent. Participants were made aware that there was only one target red square present during all target-present trials, and that the circle and squares presented in each of the four quadrants would vary in both number and location within the quadrants across trials. Shape arrays were presented until a response was made (up to 8 s). Participants were not made aware of the contingency in which target-present trials always proceeded in pairs (there were no more than two target-present trials in a row to clearly delineate target pairs and no more than three target-absent trials in a row) such that the location of the target on trial *N* always predicted the location of the target on trial $N + 1$. There were four versions of these pairings across all participants and all participants viewed all potential target pairings: (a) if the target was located in the top left quadrant on trial *N*, the target would always appear in the bottom right quadrant on trial $N + 1$, (b) if the target was located in the top right quadrant on trial *N*, the target would always appear in the top left quadrant on trial $N + 1$, (c) if the target was located in the bottom left quadrant on trial *N*,

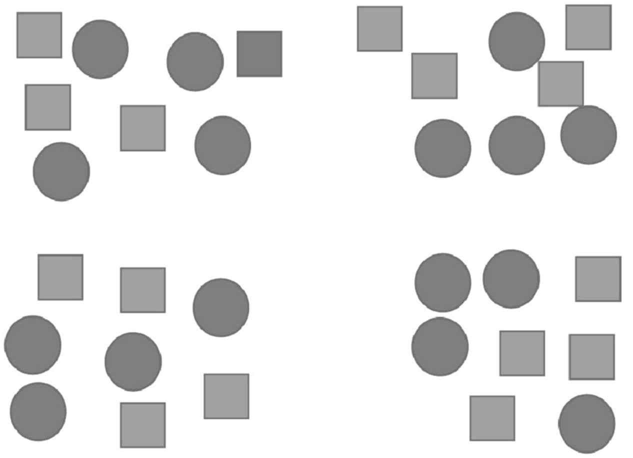

Fig. 1 Example of the search array used in Experiments 1–3. Participants were searching for the target *red square* amongst *red* and *blue circles* and *squares*

the target would always appear in the top right quadrant on trial $N + 1$, and (d) if the target was located in the bottom right quadrant on trial *N*, the target would always appear in the bottom left quadrant on trial $N + 1$. Participants were exposed to each of the four contingencies equally across blocks in a random order per each participant. No-target trials constituted 35 % of all trials.

Results and discussion

As we are interested in how implicit learning of target location alters eye movements and manual response to the target across blocks, our initial analyses includes only target-present trials (trials with a red square present; as would be expected, RTs on target-absent trials were longer than those on target-present trials) with the critical comparisons being eye movements and reaction times on trial *N* (where target location cannot be predicted based on the preceding trial) relative to trial $N + 1$ (where target location can be predicted). We first examined RT to determine if the implicit learning of these indirect statistical regularities influenced performance when responding to the target on trial $N + 1$ relative to the predictor trial *N*. We then analyzed first fixation and fixation duration to determine whether an implicit learning effect was observed in differences in RT on trial $N + 1$ relative to trial *N* due to early processes of visual selection.

Reaction time

Reaction times as a function of trial type and trial block can be found in Table 1. A 3 (block: 1st block, 2nd block, 3rd block) × 2 (target trial: *N* and $N + 1$) repeated-measures ANOVA was utilized to examine how RTs differed across blocks, and to determine whether participants were faster at responding to the target on trial $N + 1$ relative to trial *N* across the four contingencies. Unsurprisingly, there was a main effect of block, $F\ (2,\ 36) = 57.88$, $\mathrm{MSE} = 129{,}215.17$, $p < 0.001$, with RTs being faster in later blocks. Critically, there was also a main effect of target trial, $F(1, 18) = 11.37, \mathrm{MSE} = 86{,}755.38, p = 0.003$, with RTs being faster when responding to a target on a $N + 1$ trial relative to a *N* trial. The interaction between block and target trial was not significant, $F\ (2,\ 36) = 0.131, p = 0.88$.

To further examine this effect, a series of paired samples *t* test were conducted comparing RT difference across the specific blocks, as well as the differences in target trial across each block separately. With regard to block, participants were significantly faster at responding to the target in block 2 relative to block 1, $t\ (18) = 7.78$, $p < 0.001$, and block 3 relative to block 2, $t\ (18) = 4.14$, $p = 0.001$. For target trial, in block 1, participants responded faster to the target on the $N + 1$ trial relative to trial *N*, $t\ (18) = 2.12$, $p < 0.05$. The same pattern held true for block 2, $t\ (18) = 2.13$, $p < 0.05$, and block 3, $t\ (18) = 3.34$, $p < 0.001$.

Eye movements

With respect to eye movements, our initial analyses focused on first fixation time—the amount of time (ms) elapsing between the onset of the trial and the moment the participant first fixates the target quadrant. A 3 (block: 1st block, 2nd block, 3rd block) × 2 (target trial: *N* and $N + 1$) repeated-measures ANOVA was utilized to examine how first fixation time to the target quadrant differed across blocks, and to determine whether participants were faster to fixate to the target quadrant on trial $N + 1$ relative to trial *N* aggregated across the four contingencies. Unsurprisingly, there was a main effect of block, F (2, 36) = 50.17, $\mathrm{MSE} = 79{,}686.34$, $p < 0.001$, with first fixation time being faster to the target quadrant in later blocks given reductions in overall search time. Although we posited that implicit learning may make participants faster to fixate to the target quadrant on trial $N + 1$ relative to trial *N*, the main effect of target trial was not significant, $F\ (1,\ 18) = 2.21, p = 0.16$. The interaction between block and target trial was also not significant, $F\ (2,\ 36) = 0.04$, $p = 0.96$. First fixation time as a function of trial type and trial block can be found in Table 2.

In addition to examining first fixation time collapsed across conditions, we also examined each of the four contingencies individually to determine whether all contingencies were similarly processed/learned utilizing a 3 (block: 1st block, 2nd block, 3rd block) × 2 (target trial:

Table 1 Mean reaction time (ms) as a function of block and target trial in Experiment 1 through Experiment 3

	Block				
	Target trial	Block 1	Block 2	Block 3	Block 4
Experiment 1	*N*	3,681.43 (498.36)	3,151.36 (527.06)	2,817.16 (674.69)	
	N + 1	3,520.54 (494.00)	2,940.48 (512.79)	2,630.83 (722.64)	
Experiment 2	*N*	3,761.85 (737.25)	3,380.53 (522.48)	2,970.79 (529.57)	
	N + 1	3,608.92 (629.49)	3,104.05 (543.71)	3,236.40 (463.14)	
Experiment 3	*N*	3,613.44 (518.22)	2,828.54 (822.56)	2,238.19 (779.60)	1,853.87 (718.08)
	N + 1	3,512.74 (690.91)	2,494.18 (770.47)	1,804.85 (759.25)	1,575.08 (636.00)

Standard deviations appear in parentheses next to each mean. There was a significant mean difference in target detection RT to trial *N* relative to trial *N* + 1 in all comparisons with the exception of Block 1 in Experiment 2 and Experiment 3

Table 2 First fixation time as a function of block and target trial in Experiment 1 through Experiment 3

	Block				
	Target trial	Block 1	Block 2	Block 3	Block 4
Experiment 1	*N*	2,157.98 (458.93)	1,786.03 (454.92)	1,523.79 (479.14)	
	N + 1	2,112.16 (479.73)	1,709.07 (422.98)	1,457.74 (563.89)	
Experiment 2	*N*	2,129.38 (577.01)	1,982.86 (384.94)	1,682.64 (453.89)	
	N + 1	2,244.91 (611.03)	1,874.99 (433.83)	1,784.05 (383.53)	
Experiment 3	*N*	2,164.99 (413.82)	1,698.17 (636.12)	1,395.88 (526.49)	1,035.30 (578.44)
	N + 1	2,188.44 (668.34)	1,447.67 (531.06)	1,116.45 (454.20)	877.38 (422.52)

Standard deviations appear in parentheses next to each mean

N and *N* + 1) repeated-measures ANOVA per each contingency. As most participants adopted a similar scanning strategy across each trial (e.g., began in the upper left quadrant and searched in a clockwise fashion), across half of the contingencies participants fixated faster to the target quadrant on trial *N* relative to trial *N* + 1 (target located in the top left quadrant for trial *N* and bottom right for trial *N* + 1; target located in the bottom left quadrant on trial *N* and top right on trial *N* + 1; $p\text{s} < 0.04$), while the reverse pattern was observed for the other two contingencies (target located in the top right for trial *N* and top left for trial *N* + 1; target located in the bottom right for trial *N* and bottom left for trial *N* + 1; $p\text{s} < 0.02$). This effect did not change across block. We then examined first fixation time to the target quadrant on trial *N* + 1 relative to eye movement performance on trial *N* + 2. Since every pair of target trials was followed by a no-target trial, there were two critical comparisons. First, we examined first fixation time to the target quadrant on trial *N* + 1 to that same quadrant on trial *N* + 2 (no-target). Similar to our initial comparison (trial *N* relative to *N* + 1), this allows us to determine whether search differences exist when the target location is predictable (*N* + 1) vs. not predictable (e.g., not present), and also to determine whether search differences exist when the target is present vs. absent. Similar to our initial analysis above, there was no effect of target trial as participants were no faster to fixate the target quadrant on trial *N* + 1 relative to that same quadrant on trial *N* + 2, $F\ (1,18) = 0.418$, $\text{MSE} = 351{,}343.81$ $p = 0.52$ (*N* + 1: $M = 1{,}759.66$, $\text{SD} = 488.87$; *N* + 2: $M = 1{,}684.56$, $\text{SD} = 500.67$). As before, this was attributable to participants using the same general scanpath on each trial: when broken into subcontingencies, participants fixated faster to the critical quadrant on trial *N* + 1 relative to trial *N* + 2 for two of the contingencies, while the reverse pattern of result was obtained for the other two contingencies.

Next, we examined whether learning the *N*/*N* + 1 contingency influenced *N* + 2 performance in any predictable manner. Since the target location on trial *N* predicted the target location on trial *N* + 1, it is possible that participants may also anticipate that the target location on trial *N* + 1 would predict where a target might appear on trial *N* + 2 (even though a target never appears on these trials). For example, since an upper left target on trial *N* predicts a lower right target on trial *N* + 1, participants may come to expect that an upper left target on trial *N* + 1 would predict a lower right target on trial *N* + 2. Thus, we reanalyzed the first fixation time data in this manner (replacing *N*/*N* + 1 with *N* + 1/*N* + 2) but again saw no difference in first fixation time to critical quadrants, $F\ (1,18) = 0.07$, $\text{MSE} = 81{,}731.63$ $p = 0.80$ (*N* + 1: $M = 1{,}740.55$, $\text{SD} = 528.23$; *N* + 2: $M = 1{,}726.78$, $\text{SD} = 468.99$). Note

Table 3 Fixation duration as a function of block and target trial in Experiment 1 and Experiment 3

	Block				
	Target trial	Block 1	Block 2	Block 3	Block 4
Experiment 1	N	238.52 (37.50)	233.81 (32.52)	230.60 (31.84)	
	$N + 1$	233.34 (37.68)	228.72 (36.05)	225.41 (33.89)	
Experiment 3	N	244.96 (26.02)	237.51 (29.45)	231.21 (20.91)	225.62 (22.57)
	$N + 1$	234.46 (23.80)	233.55 (30.92)	227.45 (23.01)	219.88 (26.76)

Standard deviations appear in parentheses next to each mean

this analysis is only possible for the eye movement data and not the reaction time data since there is no target on trial $N + 2$. Thus, even though we obtained evidence for implicit learning as it relates to reaction times, there was no evidence that this learning led to oculomotor behavior changes related to the speed of fixating the correct target quadrant.

Finally, we examined whether fixation duration differed across blocks to determine if search became more efficient as a function of experience with the $N/N + 1$ contingencies as well as if differences were present on trial N relative to trial $N + 1$. Generally, it is expected that fixation duration will decrease over time as less effort is needed to identify and locate the target (Antes, 1974). As participants begin to search more efficiently, fixation duration goes down because less time is needed to process the non-target stimuli. Per each block, mean fixation duration was calculated for each trial (the mean duration of each individual fixation during the trial) and was then aggregated across all trial Ns and all trial $N + 1$s. A 3 (block: 1st block, 2nd block, 3rd block) × 2 (target trial: N and $N + 1$) repeated-measures ANOVA was utilized and there was a marginally significant main effect of block, where fixation duration decreased as block increased, F (2, 36) = 3.12, MSE = 192.88, $p = 0.05$. Interestingly, there was also a main effect of target trial, where fixation duration was shorter on trial $N + 1$ relative to trial N, F (1, 18) = 9.00, MSE = 84.07, $p < 0.01$. The interaction between block and target trial was not significant ($p < 0.90$; see Table 3 for means and standard deviations).

The results of Experiment 1 are consistent with the adaptive scanning hypothesis (Myers & Gray, 2010) in that participants demonstrate a search time reduction based on the learning of the statistical regularity and this seems primarily due to the same general scanpath repeating, albeit more efficiently across blocks as indicated by the reduction in fixation duration across blocks. Importantly, however, this effect is not attributable to serial scanning order as detection of a target on N does not alter the speed or likelihood with which the correct quadrant will be fixated first on $N + 1$.

Ruling out alternative explanations

Our paradigm utilized target-pair contingencies, where the location of the target on trial N predicted the location of the target quadrant on trial $N + 1$. As such, trial N was always preceded by a target-absent trial while trial $N + 1$ was always preceded by a target-present trial. It is plausible then that our results could be attributable to simple motor priming based on executing the same response on consecutive trials, whereas the response on trial N and $N + 2$ always required a different response relative to the previous trial. To address this concern, we examined whether differences existed in reaction time when comparing no-target trials preceded by other no-target trials, and no-target trials preceded by target trials, utilizing a 3 (block: 1st block, 2nd block, 3rd block) × 2 (no-target trial preceded by: no-target trial, target trial) repeated-measures ANOVA. Participants were faster responding on the no-target trial when it was preceded by a target trial ($M = 5{,}332.19$, SD = 993.77) relative to a no-target trial ($M = 5{,}503.29$, SD = 989.22; $p < 0.01$) meaning that simple response priming could not account for the differences found in reaction time in regard to trial N relative to trial $N + 1$.

It is also possible, given that the location of the target on trial $N + 1$ was always in a different quadrant than the target quadrant on trial N, that participants recorded faster reaction times on trial $N + 1$ due to inhibition of the previous trial quadrant to avoid binding of target and location. If the previous trial quadrant was avoided on trial $N + 1$, then only three quadrants would need to be searched relative to four on trial N. To address this concern, we examined whether first fixation time differed to the target quadrant on trial N relative to that same quadrant on trial $N + 1$ (e.g., if the upper left quadrant was the target quadrant on trial N, how quickly is the upper left quadrant fixated on trial $N + 1$). A 3 (block: 1st block, 2nd block, 3rd block) × 2 (target quadrant in trial N for trial N and trial $N + 1$) repeated-measures ANOVA indicated that participants were faster to fixate to the trial N target quadrant on trial $N + 1$ ($M = 1{,}154.05$, SD = 388.43) relative to on trial N ($M = 1{,}867.77$, SD = 452.96; $p < 0.001$). This means that participants were actually quicker to return to the previous target location as opposed to inhibiting that location.[1]

Finally, it is possible that differences observed in reaction time and, in particular, first fixation time when comparing trial N relative to trial $N + 1$ exist due to short-term feature priming. While we cannot directly rule out this possibility, the influence of feature priming usually occurs when the entire display is visible and attention and eye movements are biased toward the critical feature from the previous trial (e.g., Becker & Horstmann, 2009; Kristjansson, Wang, & Nakayama, 2002). Furthermore, as Becker and Horstmann (2009) demonstrate, feature priming normally affects only the probability of detecting the target as the first item in the following display in conjunction search. Given that our displays were processed through a gaze-contingent window (with no visual information visible at fixation), however, attention and eye movements could not be influenced by the presence of critical features given until they fixated the general vicinity of the target. Moreover, given that the target was always the same and the critical color and shape features were present on every trial—albeit in different combinations—it seems more likely that participants would adopt a single target template (e.g., attentional control settings) that would not necessarily benefit trial $N + 1$ performance differentially relative to trial N performance.

Experiment 2

Although in Experiment 1, participants were faster to respond to the target on the predicted $N + 1$ trials relative to the predictor N trial—and therefore exhibited evidence of implicit learning across blocks—oculomotor behavior was unaffected for all measures other than fixation duration. In examining first fixation time and fixation order in Experiment 1, however, we noticed that many participants adopted a similar search strategy on each trial (e.g., searching in a clockwise fashion) meaning that the manner in which eye movements could change due to implicit learning might have been overridden by the strategy of always adopting the same general scanpath. The purpose of Experiment 2 was to determine whether an influence of implicit learning on search behavior would be evident if participants were required to alter their scanning strategy from trial to trial. Perhaps the requirement to search differently across trials would give way to biases based on learned regularities.

Method

Participants

Eighteen undergraduate students from the University of Nebraska-Lincoln participated in the study and received course credit for their participation. All participants had normal or corrected-to-normal vision and were naïve to the purpose of the study that took place in a single 60-min session.

Apparatus and procedure

The procedure was identical to Experiment 1 with the exception that participants were instructed to vary their search strategy across trials (e.g., do not always look at the same quadrant first). Participants were not explicitly instructed on how to search for the target, but were simply told to vary their approach to scanning as much as possible, with the expectation that this would eliminate visual scan similarity across trials and might lead to biases in first fixation as a function of implicit learning.

Results and discussion

Reaction time

A 3 (block: 1st block, 2nd block, 3rd block) × 2 (target trial: N and $N + 1$) repeated-measures ANOVA was utilized to examine differences in RT across blocks, and to examine whether participants were faster to respond to the target in the predicted trial $N + 1$ relative to trial N. The means and standard deviations are presented in Table 1. There was once again a main effect of block, F (2, 34) = 15.25, MSE = 218,058.37, $p < 0.001$, with RTs being faster across each experimental block. There was no main effect of target trial, F (1, 17) = 0.65, $p = 0.43$, though, unexpectedly, the interaction between block and target trial was significant, F (2, 34) = 8.35, MSE = 87,046.70 $p = 0.001$. To further examine this effect, a series of paired samples t tests were conducted comparing RT differences across the specific blocks, as well as the differences in target trial across each block separately. With regard to block, participants were significantly faster at responding to the target in block 2 relative to block 1, t (17) = 4.88, $p < 0.001$, but there was no difference in RT across block 2 and block 3, t (17) = 1.50, $p = 0.15$. For target trial, in block 2, participants responded faster to the target on the $N + 1$ trial relative to trial N, t (17) = 3.44, $p = 0.003$. However, this pattern was reversed in block 3, t (17) = 2.32, $p = 0.03$. In block 1, participants were faster to respond on trial $N + 1$ relative

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[1] Each of the additional analyses reported here were conducted for Experiment 2 and Experiment 3. We only included these analyses in Experiment 1, as this experiment was the only experiment demonstrating implicit learning, though the results across all three experiments ruled out the proposed alternative explanations of the results.

to trial N though this mean difference was not significant, $t\ (17) = 1.31$, $p = 0.21$. Thus, the requirement to alter scan strategy in a top-down manner might have erased the learning effects we observed in the previous experiment.

Eye movements

A 3 (block: 1st block, 2nd block, 3rd block) × 2 (target trial: N and $N + 1$) repeated-measures ANOVA was once again utilized to examine whether participants were faster to fixate to the target quadrant on trial $N + 1$ relative to trial N. Unsurprisingly, there was a main effect of block, $F\ (2, 32) = 9.72$, MSE = 181,165.75, $p < 0.01$, with first fixation time being faster to the target quadrant in later blocks. The main effect of target trial, $F\ (1, 16) = 0.44$, $p = 0.52$ and the interaction between block and target trial was not significant, $F\ (2, 32) = 2.40$, $p = 0.11$. First fixation time as a function of trial type and trial block can be found in Table 2.

Requiring participants to alter the manner in which they search for the target after each trial did not lead to oculomotor biases based on implicit learning but instead extinguished the learning effects observed in Experiment 1. However, it is possible that the instruction to alter scan paths may have simply overridden the more subtle effects of implicit learning or the expression of what has been learned. Previous research has suggested that the expression of what is implicitly learned in a serial reaction time task is altered under dual-task relative to single-task conditions (e.g., Frensch, Buchner, & Lin, 1994; Frensch & Miner, 1994). For example, Frensch, Lin, and Buchner (1998) have demonstrated that a reduction in learning might not actually be taking place in dual-task conditions. These researchers had participants complete a serial reaction task along with a tone-counting task, with the results indicating that implicit learning was impaired relative to the single-task alone condition. When the secondary tone-counting task was removed during the task, however, participants exhibited the same amount of implicit sequence knowledge as the single-task condition. It therefore appears that the addition of a secondary task load may have very little impact on actual implicit learning itself, but impacts performance on an implicit learning task while the secondary task is being conducted. In the current experiment, we never removed the requirement to alter scan paths since our intent was to determine whether biases emerged when identical scanpaths are avoided. Removing the requirement to alter scanpaths may have resulted in implicit learning but there is no reason to think that this effect would manifest any differently than in E1, meaning no evidence of any change in oculomotor behavior.

Experiment 3

The purpose of Experiment 3 was to determine the degree to which making participants aware that a contingency exists influences eye movements. Thus, at the beginning of the experiment, participants were told that there was a contingency which, if they figured it out, would decrease the amount of time it would take them to perform the task. If after two blocks of trials they had not figured the contingency out, they were explicitly told that targets appear in pairs and that the location of the target on the first trial of the pair predicted the location of the target on the next trial. This allowed us to determine whether oculomotor behavior was influenced by explicit knowledge of the contingency.

Method

Participants

Seventeen undergraduate students from the University of Nebraska-Lincoln participated in the study and received course credit for their participation. All participants had normal or corrected-to-normal vision and were naïve to the purpose of the study that took place in a single 60-min session.

Apparatus and procedure

Experiment 3 was identical to the previous experiments, with the exception that participants were instructed before the experiment began that the target location was contingent on a series of patterns. Participants were told that the faster they solve the contingency, the faster the experiment would conclude. At the conclusion of block 2, the experimenter further instructed participants that the red square location of the previous trial (trial N), predicting the target location in the next trial (trial $N + 1$). To ensure a sufficient number of trials once participants were aware of the contingency, we added a forth block of trials, where each block consisted of 100 trials.

Results and discussion

Reaction time

A 4 (block: 1st block, 2nd block, 3rd block, 4th block) × 2 (target trial: N and $N + 1$) repeated-measures ANOVA was utilized to examine how RTs differed across blocks, and to determine whether participants were faster at responding to the target red square on trial $N + 1$ relative to trial N across the four $N + 1$ contingencies. The means and standard deviations are presented in Table 1. Unsurprisingly, there was a main effect of block, F (3, 48) = 57.42, MSE = 395,134.30, $p < 0.001$, with RTs being faster during later blocks. Critically, there was also a main effect of target trial, F (1, 16) = 10.94, MSE = 255,742.24, $p = 0.004$, with RTs being faster when responding to a target on a $N + 1$ trial relative to a N trial. The interaction between block and target trial was not significant, F (3, 48) = 1.26, $p = 0.30$.

To further examine this effect, a series of paired samples t test were conducted comparing RT difference across the specific blocks, as well as the differences in target trial across each block separately. With regard to block, participants were significantly faster at responding to the target in block 2, t (16) = 6.23, $p < 0.001$, relative to block 1. Further, participants were faster at responding to the target in block 3, t (16) = 4.61, $p < 0.001$, relative to block 2 and block 4 relative to block 3, t (16) = 3.04, $p < 0.01$. For target trial, in block 2 participants responded faster to the target on the $N + 1$ trial relative to trial N, t (16) = 2.51, $p = 0.02$. The same pattern held true for block 3, t (16) = 2.35, $p = 0.03$, and block 4, t (16) = 2.53, $p = 0.02$. There was no mean difference in response to the target on the $N + 1$ trial relative to trial N in block 1, t (16) = 0.90, $p = 0.38$.

Eye movements

A 4 (block: 1st block, 2nd block, 3rd block, 4th block) × 2 (target trial: N and $N + 1$) repeated-measures ANOVA was once again utilized to examine whether participants were faster to fixate to the target quadrant on trial $N + 1$ relative to trial N. There was a main effect of block, F (3, 30) = 23.86, MSE = 257,585.92, $p < 0.001$, with first fixation time being faster to the target quadrant in later blocks. Critically, there was also a main effect of target trial, F (1, 10) = 6.60, $p = 0.03$, where participants were faster to fixate to the target quadrant on trial $N + 1$ relative to trial N. The interaction between block and target trial was not significant, F (3, 30) = 1.41, $p = 0.26$. In addition, when comparing the likelihood of fixating the target quadrant on trial $N + 1$ relative to that same quadrant on no-target trials, participants were always faster to fixate on target-present $N + 1$ trials (all $ps < 0.02$) across the four contingencies. Thus, there is clear evidence that explicit learning impacted eye movements in a manner not observed for implicit learning. First fixation time as a function of trial type and trial block can be found in Table 2.

As in Experiment 1, we once again examined fixation duration to determine if search became more efficient in terms of block and when comparing trial N relative to trial $N + 1$. A 4 (block: 1st block, 2nd block, 3rd block, 4th block) × 2 (target trial: N and $N + 1$) repeated-measures ANOVA was conducted. There was a main effect of block, where fixation duration decreased as block increased, F (3, 48) = 7.14, MSE = 261.30, $p < 0.001$. There was also a main effect of target trial, where fixation duration was always shorter on trial $N + 1$ relative to trial N, F (1, 16) = 9.96, MSE = 122.44, $p < 0.01$. The interaction between block and target trial was not significant ($p = 0.40$; see Table 2 for the means and standard deviations).

As in Experiment 1, participants learned the statistical contingencies, as reaction times were faster on trial $N + 1$ compared to trial N across the four blocks. Further, participants exhibited shorter fixation durations on trial $N + 1$ relative to trial N demonstrating increased efficiency of search. When learning is explicit, however, we also observed changes in first fixation time over trials where participants were instructed that a series of contingencies exist predicting target location. As such, search strategy appears to be altered when knowledge of contingencies is explicitly known, but implicit learning of these same contingencies does not lead to accompanying changes in first fixation time.

Discussion

The purpose of the present study was to examine whether oculomotor behavior is systematically altered across blocks when participants are exposed to global statistical properties within distractor/target search configurations. It is well established that in explicit learning, individuals direct eye movements to highly probable target locations while ignoring locations that are most likely void of the target (i.e., Castelhano & Henderson, 2007; Malcolm & Henderson, 2010). The present study examined whether eye movement patterns are influenced when environmental probabilities are implicitly learned given a lack of clarity regarding whether implicit learning affects search behavior or whether this learning influences factors independent of eye movements (e.g., response criterion). We addressed this question utilizing a novel paradigm where we examine temporal-spatial contextual cueing effects with the target location on one trial predicts the location of the target on the next trial.

While the response time to the target was faster on the predicted trial $N + 1$ relative to the predictor trial N in Experiment 1 and Experiment 3, eye movements remained unchanged as it relates to first fixation in the first experiment. Specifically, participants were not faster or more likely to fixate to the target quadrant on trial $N + 1$ relative to trial N. Despite no evidence of change in first fixation, evidence for implicit learning was apparent as reaction times were fastest on trials where target location was predictable. Furthermore, fixation duration decreased across blocks demonstrating greater efficiency of search over time. Of further interest, participants demonstrated shorter fixation durations on trial $N + 1$ relative to trial N. When participants were explicitly made aware of the contingency in Experiment 3, however, changes in first fixation were observed, with participants being faster to fixate the target quadrant on trial $N + 1$. Moreover, the same pattern of fixation duration on trial $N + 1$ was observed in both Experiments 1 and 3. It therefore appears then that when participants are explicitly aware that a contingency is present within the distractor/target search configurations, they are more likely to direct their eye movements toward locations where the target is highly likely to appear, ignoring lower probability locations. When participants are unaware of the target-pair contingency, implicit learning still occurs without changes in first fixation. Instead, participants seem to adopt a similar visual scan across trials with only the speed of fixation duration changing over time. We determined that the changes on trial $N + 1$ relative to trial N in terms of reaction time and first fixation time cannot be attributed to response priming, short-term feature priming nor inhibition of the target quadrant. It is worth noting, however, that participants may not have been learning something as complex as all four-target contingencies. Rather performance might have been influenced by something more fragmental, such as learning that targets always appear in pairs with the second target never appearing in the same general location as the first (our additional analyses are inconsistent with this, however). Regardless of the level at which the contingency was learned, it is clear that performance was influenced by implicit learning in terms of reaction time, but not oculomotor behavior.

It has been repeatedly demonstrated that with time and experience, individuals are better at visual search, as indexed by reduced search time and less effort exerted (i.e., Chun & Jiang, 1998). The results of the current study are consistent with the adaptive scanning hypothesis (Myers & Gray, 2010) in that participants demonstrate a search time reduction based on the learning of the statistical regularity—in addition to practice with the task given that participants also speed up on N trials with each subsequent block. These results seem generally consistent with the notion that participants tend to repeat the same general scanpath during search, and it is the speed with which they carry out scanning that increases performance. This is in line with the findings of Myers and Gray (2010) who showed that during repeat search arrays, both efficiency and visual scan similarity increase. Reusing similar scanpaths across trials seems practical in the current paradigm as part of the display was occluded via the gaze-contingent window. As a result, participants were unable to utilize global target features to facilitate search. Also, by having the same general scanpath repeat across trials, search may have been facilitated due to decreased saccade planning. Interestingly, when forcing participants to alter their visual scan strategy after each trial (Experiment 2), implicit learning was hindered. It therefore appears then that eliminating visual scan similarity can actually impact learning in contextual visual search, possibly due to more effort expended on eye movement patterns relative to learning the global statistical context.

It also appears that set size can influence the manner in which we search repeat displays. In a contextual cueing paradigm where participants had to find the target “T” and judge its’ orientation amongst 11 distractors “Ls” utilizing serial search (Peterson & Kramer, 2001), participants demonstrated fewer fixations and a greater likelihood to fixate first to the target in repeat relative to novel search displays. Importantly, however, this was not always the case in certain repeat trials, and oftentimes the benefits of contextual cueing did not occur until later in the search process, when participants eventually recognized the repeat search display. Therefore, the effects of contextual cueing on the guidance of attention were only effective in a limited amount of trials. It is possible that due to the much larger distractor/target search configuration utilized in the present study, as well as the more difficult contextual cue we used (four $N + 1$ contingencies relative to simply repeating search displays), participants were no more likely to fixate to the target quadrant on trial $N + 1$ relative to trial N in Experiment 1. However, as participants were faster to respond to the target on trial $N + 1$ relative to trial N, recognition may have occurred later in the search process on the predicted trial.

Utilizing another contextual cueing paradigm, Kunar, Flusberg, Horowitz, and Wolfe (2007) argued that response selection rather than the implicit learning of context results in the advantages shown in RT for repeat relative to novel search displays (but see Zhao et al., 2012 for an alternative result). It is not that participants are searching more efficiently across repeat search displays, but instead the benefits of implicit learning are due partially to faster response execution. When interference was added to the response selection stage of finding and responding to the target, contextual cueing effects were eliminated. Similar to the current study, we also found little evidence of increased search efficiency across trials when trial N predicted the target quadrant on trial $N + 1$ in terms of first fixation time. As Kunar et al. argued, participants might have shown a reduction in RT on the predicted trial as a result of a lower response threshold once the target was detected.

In summary, participants were faster to detect the target on trial $N + 1$ compared to trial N in a implicit contextual cueing search array (Experiment 1), as well as when we informed participants a contingency was present

(Experiment 3), and efficiency in search increased over time shown in fixation duration. However, changes in first fixation were only present in Experiment 3, after participants were informed that the preceding location of the target predicts the location of the subsequent target in block 3. In the current paradigm therefore, it appears then that eye movements as it relates to first fixation to the target quadrant are unaffected by implicit learning over time, until this knowledge becomes explicit. Future research is needed to further the understanding of implicit learning and eye movements, to precisely determine why we are able to respond to a target faster in an implicitly learned contextual display relative to a novel one.

References

Antes, J. R. (1974). The time course of picture viewing. *Journal of Experimental Psychology, 103*, 62–70.

Becker, S. I., & Horstmann, G. (2009). A feature-weighting account of priming in conjunction search. *Attention, Perception, and Psychophysics, 71*, 258–272.

Biederman, I. (1972). Perceiving real-world scenes. *Science, 177*, 77–80.

Carrasco, M., McLean, T. L., Katz, S. M., & Frieder, K. S. (1998). Feature asymmetries in visual search: effects of display duration, target eccentricity, orientation and spatial frequency. *Vision Research, 38*(3), 347–374.

Castelhano, M. S., & Henderson, J. M. (2007). Initial scene representations facilitate eye movement guidance in visual search. *Journal of Experimental Psychology: Human Perception and Performance, 33*, 753–763.

Chun, M. M., & Jiang, Y. (1998). Contextual cueing: implicit learning and memory of visual context guides spatial attention. *Cognitive Psychology, 36*(1), 28–71.

D'Zmura, M. (1991). Color in visual search. *Vision Research, 31*, 951–966.

Dick, M., Ullman, S., & Sagi, D. (1987). Parallel and serial processes in motion detection. *Science, 237*, 400–402.

Dodd, M. D., Van der Stigchel, S., & Hollingworth, A. (2009). Novelty is not always the best policy: inhibition of return and facilitation of return as a function of visual task. *Psychological Science, 20*, 333–339.

Druker, M., & Anderson, B. (2010). Spatial probability aids visual stimulus discrimination. *Frontiers in Human Neuroscience, 4*(63), 1–10.

Fiser, J., & Aslin, R. N. (2002). Statistical learning of higher-order temporal structure from visual shape sequences. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 28*(3), 458–467.

Foster, D. H., & Ward, P. A. (1991). Asymmetries in oriented-line detection indicate two orthogonal filters in early vision. *Proceedings of the Royal Society of London B, 243*, 75–81.

Frensch, P. A., Buchner, A., & Lin, J. (1994). Implicit learning of unique and ambiguous serial transitions in the presence and absence of a distractor task. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 20*, 567–584.

Frensch, P. A., Lin, J., & Buchner, A. (1998). Learning vs. behavioral expression of the learned: The effects of a secondary tone-counting task on implicit learning in the Serial Reaction Task. *Psychological Research, 61*, 83–98.

Frensch, P. A., & Miner, C. S. (1994). Individual differences in short-term memory capacity on an indirect measure of serial learning. *Memory and Cognition, 22*, 95–110.

Geng, J. J., & Behrmann, M. (2005). Spatial probability as an attentional cue in visual search. *Perception and Psychophysics, 67*(7), 1252–1268.

Jiang, Y. V., Swallow, K. M., & Rosenbaum, G. M. (2013a). Guidance of spatial attention by incidental learning and endogenous cuing. *Journal of Experimental Psychology: Human Perception and Performance, 39*, 285–297.

Jiang, Y. V., Swallow, K. M., Rosenbaum, G. M., & Herzig, C. (2013b). Rapid acquisition but slow extinction of an attentional bias in space. *Journal of Experimental Psychology: Human Perception and Performance, 39*, 87–99.

Kabata, T., & Matsumoto, E. (2012). Cueing effects of target location probability and repetition. *Vision Research, 73*, 23–29.

Kristjansson, A., Wang, D., & Nakayama, K. (2002). The role of priming in conjunctive visual search. *Cognition, 85*, 37–52.

Kunar, M. A., Flusberg, S. J., Horowitz, T. S., & Wolfe, J. M. (2007). Does contextual cuing guide the deployment of attention. *Journal of Experimental Psychology: Human Perception and Performance, 33*(4), 816–828.

Malcolm, G. L., & Henderson, J. M. (2010). Combining top-down processes to guide eye movements during real-world scene search. *Journal of Vision, 10*(2), 1–11.

McLeod, P., Driver, J., & Crisp, J. (1988). Visual search for conjunctions of movement and form is parallel. *Nature, 332*, 154–155.

Moraglia, G. (1989). Visual search: spatial frequency and orientation. *Perceptual and Motor Skills, 69*, 675–689.

Myers, C. W., & Gray, W. D. (2010). Visual scan adaptation during repeated visual search. *Journal of Vision, 10*(8), 1–14.

Peterson, M. S., & Kramer, A. F. (2001). Attentional guidance of the eyes by contextual information and abrupt onsets. *Perception and Psychophysics, 63*(7), 1239–1249.

Rosenholtz, R. (2001). Search asymmetries? What search asymmetries? *Perception and Psychophysics, 63*, 476–489.

Saffran, J. R. (2002). Constraints on statistical language learning. *Journal of Memory and Language, 47*, 172–196.

Smith, T. J., & Henderson, J. M. (2009). Facilitation of return during scene viewing. *Visual Cognition, 17*, 1083–1108.

Stadler, M. A. (1989). On learning complex procedural knowledge. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15*, 1061–1069.

Theeuwes, J. (1992). Perceptual selectivity for color and form. *Perception and Psychophysics, 51*(6), 599–606.

Theeuwes, J. (1994). Stimulus-driven capture and attentional set: selective search for color and visual abrupt onsets. *Journal of Experimental Psychology: Human Perception and Performance, 20*(4), 799–806.

Tseng, Y. C., & Li, C. S. (2004). Oculomotor correlates of context-guided learning in visual search. *Perception and Psychophysics, 66*(8), 1363–1378.

Wolfe, J. M., & Horowitz, T. S. (2004). What attributes guide the deployment of visual attention and how do they do it? *Nature Reviews Neuroscience, 5*, 1–7.

Zhao, G., Liu, Q., Zhou, P. L., Jiao, J., Li, H., & Sun, H. J. (2012). Dual-state modulation of the contextual cueing effect: evidence from eye movements during task-relevant observation. *Journal of Vision, 12*(6), 1–13.

Ziessler, M. (1994). The impact of motor responses on serial pattern learning. *Psychological Research, 57*, 30–41.