Research Article

PROBABILITY CUING OF TARGET LOCATION FACILITATES VISUAL SEARCH IMPLICITLY IN NORMAL PARTICIPANTS AND PATIENTS WITH HEMISPATIAL NEGLECT

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Abstract—*We explored how variability in the probability of target locations affects visual search in normal individuals and in patients with hemispatial neglect, a deficit in attending to the contralesional side of space. Young and elderly normal participants responded faster when targets appeared in the more probable region than when targets appeared in the less probable region. Similarly, patients were sensitive to the distribution of targets, even in the neglected field. Although the attentional gradient that characterizes neglect was not eliminated, the response facilitation due to the probability distribution was proportionate to that of control participants and equal in magnitude across the neglected field. All participants exploited the uneven distribution of targets to enhance task performance without explicit instructions to do so or awareness of biases in their behavior. These results suggest that attentional orientation and sensitivity to external probabilities are possibly dissociable. An early sensory and a late motor mechanism are postulated as possibly being involved in the observed probability-matching behavior of participants.*

Despite their inability to articulate the regularities that drive their behavior, normal participants are able to exploit the statistical contingencies that determine the location of a visual target (Chun & Jiang, 1998; Hoffmann & Kunde, 1999; Lewicki, Czyzewska, & Hoffman, 1987; Maljkovic & Nakayama, 1996; Mayr, 1996). For example, in Chun and Jiang's (1998) experiments, participants demonstrated no explicit awareness of the relationship between targets and the distractor context, but nevertheless responded faster to targets that appeared in the same distractor configuration than to targets in novel configurations. In fact, people appear to be sensitive to repetitions in target location over approximately five to eight intervening trials even when there is no probability manipulation (Maljkovic & Nakayama, 1996). These findings are consistent with prior data suggesting that probabilistic distributions in target locations are related to performance optimization given limited attentional capacity (Shaw & Shaw, 1977).

Indeed, the ability to track statistical probabilities linking behavior to reward appears to be ubiquitous in animal species. The *matching law* characterizes the absolute rate of response as a linear function of the frequency of reinforcement. In one of the earliest examples, Herrnstein (1961) demonstrated that the frequency with which White Carneaux pigeons pecked at each of two response keys was commensurate with the reinforcement schedule at each key. Although different reinforcement paradigms result in under- or overmatching, the ranking of responses in correspondence with the available reinforcement hierarchy is well established (e.g., Baum, 1979; Greggers & Mauelshagen, 1997).

Similarly, the A-not-B error exhibited by infants can be thought of as an inability to inhibit the most probabilistic response associated with reward. Smith, Thelen, Titzer, and McLin (1999) have argued that the A-not-B error is caused by a directional bias in motor planning due in part to the history of looking and reaching to A during the preceding trial (or trials). Because infants have immature control systems, a brief visual input signaling the B trial is too weak to overcome the motor bias. However, if the visual stimulus at B is salient, it can pull the motor response toward that location (Smith et al., 1999). This suggests that although mechanisms supporting simple matching behaviors may be modulated by attentional orientation, they may also operate independently.

The collection of results from human and nonhuman species implicates an evolutionarily primitive mechanism that is sensitive to environmental regularities that result in behavioral success. The first goal of the present study was to explore whether adult human participants match their behaviors to implicit regularities in target location during a visual search task. Because we were particularly interested in the consequences of the probabilistic distribution of targets on attentional orientation, our second goal was to explore whether individuals with hemispatial neglect, a deficit in attentional orienting, are nevertheless able to exploit these contingencies in the same way as normal participants. Many studies have demonstrated a significant impairment in the visual search abilities of neglect patients (Aglioti, Smania, Barbieri, & Corbetta, 1997; Behrmann, Ebert, & Black, 2002; Eglin, Robertson, & Knight, 1989; Esterman, McGlinchey-Berroth, & Milberg, 2000; Riddoch & Humphreys, 1987).

The study of neglect patients provides a natural experiment for exploring whether behavioral sensitivity to stimulus probabilities is distinguishable from attentional orienting. If the behavior of patients can be modulated by simple regularities in target location without altering the qualitative pattern of their neglect, it would lead to an interesting dissociation between biased tonic attentional orientation and intact probability matching. This would add to current understanding of the mechanisms involved in the spatial orientation of attention and behavior.

In summary, we report here the findings from two experiments in which a visual search task was used to assess behavioral changes when targets were more likely to appear in locations on one half of the display compared with the other half. The results indicate that the behaviors of both normal and patient populations reflect sensitivity to the statistical contingencies. Despite the obvious ability to exploit these contingencies, participants reported being unaware of the uneven distribution of target locations. The complementary data from the normal and brain-damaged subjects provide converging constraints on understanding how visual search proceeds and how statistical regularities modulate the spatial orienting network.

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GENERAL METHOD

Design

The stimuli were gray (16.9 cd/m^2) letters on a green (52.8 cd/m^2) background. The letters *L* and *F* were targets, and *T* and *E* were distractors. A target was present on every trial. There were 18 possible locations, formed by a grid of 6 vertical columns by 3 horizontal rows. Six letters appeared on each trial, one in each column. The distance between letters in adjacent columns was at minimum 5 cm and at maximum 17 cm. The screen subtended 38.5° of visual angle, and each letter subtended 0.7°, if located centrally. Participants responded by pressing one button for *L* targets and another for *F* targets. Stimulus presentation and data collection were controlled using PsyScope (Cohen, MacWhinney, Flatt, & Provost, 1993). A PsyScope-compatible button box was used to collect response times (RTs).

The probability manipulation was implemented across two conditions that appeared sequentially in separate blocks of trials. In the *baseline* condition, targets were equally likely to appear in any of the six columns. In the *uneven* condition, targets appeared on one half of the screen (e.g., columns 1–3) with 80% probability and on the other half (e.g., columns 4–6) with 20% probability. The target was equally likely to appear in all possible locations within the selected screen side. The screen side containing 80% of the targets was counterbalanced across normal subjects (left, right) and always occurred on the left for neglect patients. No mention of the probability manipulation was made at the beginning of the experiment, and participants were simply instructed to indicate which target was present as quickly and accurately as possible.

Procedure

A typical trial proceeded as follows: First, a number (1–9) appeared at the center of the screen, and participants reported the number out loud. This procedure was adopted so that subjects always began the trial with central fixation. Immediately after the correct number was reported, the experimenter advanced the screen to the search display. Participants had to respond with a button press, and if no response was made within 30 s, the next trial was automatically initiated. Auditory feedback was provided on incorrect trials. The baseline condition was always run prior to the uneven condition in order to minimize learning effects on baseline performance.

To gauge their awareness of the probability manipulation, at the end of the experiment we asked participants, “Did you feel that the target was more likely to appear in one location or region, or did you feel that targets were well distributed?” Responses were recorded.

EXPERIMENT 1

Participants

Sixteen undergraduates (8 female, ages 18–22) from Carnegie Mellon University (CMU) participated for course credit. Nine elderly participants (5 female) with no history of neurological illness (ages 59–80) were recruited from the Academy of Lifelong Learning at CMU and volunteered to participate. Both age groups were included because the patients who participated in Experiment 2 were elderly and obtaining data from a nonneurological age-matched group is a critical control for understanding findings from the patient population (Curran, Hills, Patterson, & Strauss, 2001).

All participants were right-handed and had normal or corrected-to-normal vision. All testing was conducted at CMU. Participants completed 72 and 225 trials in the baseline and uneven conditions, respectively.

Results

Error responses constituted an average of 2.5% and 1% of the data for the young and elderly subjects, respectively. RTs more than 2 *SD*s from the condition mean of the correct trials were excluded. This resulted in the elimination of 5.1% of trials on average for the young participants and 5.2% of trials for the elderly participants. RT analyses were based on cell means from the remaining trials. To determine whether counterbalancing screen side across participants affected performance in the uneven condition, for each population we conducted an initial analysis with the between-participants factor of probability assignment (left, right) and the within-participants factor of screen-side contingency (80%, 20%). Probability assignment and screen side did not interact in either population, $F(1, 14) = 2.69$, $p > .05$, for young participants and $F(1, 7) = 0.06$, $p > .05$, for elderly participants. Henceforth, we refer to the side containing 80% of the targets as “left” (i.e., columns 1–3) and the side containing 20% of the targets as “right” (i.e., columns 4–6) to be consistent with the design of Experiment 2, conducted with neglect patients.

A Population (elderly, young) × Probability Condition (baseline, uneven) × Column (1–6) repeated measures analysis of variance (ANOVA) was performed. Because there was no three-way interaction, population was collapsed in the remaining analyses. The result of interest is the significant interaction between probability condition and column, $F(5, 115) = 4.60$, $p < .01$. Using the Bonferroni-corrected significance level of .008, pair-wise comparisons between corresponding columns in the two probability conditions revealed significant differences in all columns except 5, which showed the same trend as the other columns (baseline column mean − uneven column mean was 369.39 for column 1, 356.61 for column 2, 328.84 for column 3, 238.97 for column 4, 160.14 for column 5, and 165.1 for column 6; see Fig. 1). However, because the two probability conditions were always run in sequence, it was difficult to determine whether decreases in RT were due to general practice effects, the probability manipulation, or both. A comparison of the RT difference across columns within each probability condition provided further answers.

For each probability condition, a repeated measures ANOVA with the within-participants factor of column was significant, $F(5, 120) = 7.87$, $p < .01$, for the baseline condition and $F(5, 120) = 28.94$, $p < .01$, for the uneven condition.[1] Using the Bonferroni-corrected significance level of .017, pair-wise comparisons between columns of equivalent visual angle (i.e., columns 1 and 6, 2 and 5, 3 and 4) revealed the following: In the baseline condition, none of the column pairs differed significantly (mean differences: column 6 – column 1 = 124.14 ms; column 5 − column 2 = 50.40 ms; column 4 − column 3 = 29.07 ms). In the uneven condition, however, columns 1 and 2 were significantly different from columns 6 and 5, respectively (mean differences: column 6 − column 1 = 328.43 ms; column 5 − column 2 = 246.86 ms; column 4 − column 3 = 111.94 ms). This comparison confirmed that targets in the left-most columns were detected more quickly than

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[1] The significant main effect for the baseline condition comes from comparisons between columns of different visual angles that are not relevant to the present discussion (e.g., columns 4 and 6).

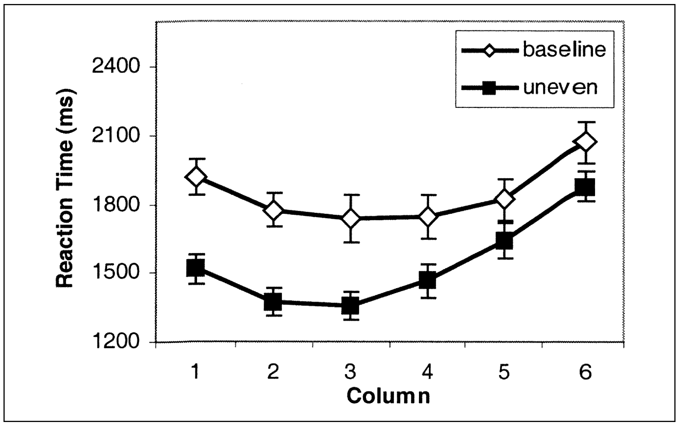

Fig. 1. Mean reaction time as a function of the target's column location in Experiment 1, which included both young and elderly participants. Results are shown separately for the baseline and uneven conditions. Vertical bars indicate standard error.

targets in the right-most columns only when the statistics governing target location were biased toward the left side of the screen.

Twelve of the 16 undergraduate participants and all of the elderly participants reported having no awareness of the probability distribution at the end of the experiment. When the 4 participants who reported some awareness of the contingency manipulation were excluded from the Probability Condition × Column analysis, all interactions and pair-wise comparisons of interest remained the same, $F(5, 100) = 3.60$, $p < .01$. This suggests that the results were not due to explicit anticipation of target location at the beginning of each trial, but rather that the spatial contingencies were being coded implicitly. From these data, we conclude that young and elderly normal participants are sensitive to the probability distribution of target objects, even when the distribution is over a region that includes several locations and when there is no explicit awareness of the contingency. We take these results to be an important demonstration of how a flexible and adaptive orienting system may direct attention optimally in response to statistical contingencies in the visual field.

EXPERIMENT 2

Although participants in the preceding experiment showed speeded responses to targets in the more probable region, it is unclear whether their ability to do so relied on an intact attentional system. In order to explore whether the observed probability matching could be supported by an orienting mechanism that is dissociable from that of the putative attentional system, we turned to patients with hemispatial neglect.

Hemispatial neglect is an acquired deficit characterized by a failure to orient attention to the contralesional side of space. Although damage to the temporal-parietal junction is the most frequent neural concomitant (Karnath, Ferber, & Himmelbach, 2001), other lesions within the distributed attentional network, including lesions in frontal, superior temporal, thalamic, and other subcortical regions, can also give rise to neglect (Kerkhoff, 2001; Mesulam, 1999). Left neglect is more common and more severe than right neglect, and we refer to neglect as left-sided throughout this article. Patients with hemispatial neglect are most often unaware of their orienting deficit and apparently do not develop compensatory strategies; for example, eye movement studies have revealed that first eye movements are to the ipsilesional, right side, and that ipsilesional fixations are longer and more frequent than contralesional fixations (Behrmann, Watt, Black, & Barton, 1997; Ishiai, Furukawa, & Tsukagoshi, 1987). Another well-established property of neglect is that it obeys a left-right gradient such that performance is incrementally poorer as the target is located further leftward (Heilman, Bowers, Valenstein, & Watson, 1987; Kinsbourne, 1987).

Interestingly, despite these orienting deficits, there is evidence that patients with neglect are able to exploit explicit spatial cues such as arrows indicating the target location or verbal instructions to orient leftward (Halligan, Manning, & Marshall, 1991; Lin, Cermak, Kinsbourne, & Trombly, 1996; Riddoch & Humphreys, 1983). Neglect patients also exhibit sensitivity to the statistical probabilities governing the appearance of targets in different reference frames (Behrmann & Tipper, 1999). In Experiment 2, we examined the impact of statistical regularities of target location as an orienting cue in relation to the spatial gradient of neglect behavior.

Participants

One female and 6 male patients with right-hemisphere brain damage participated (see Table 1). Neglect was diagnosed on a standard neuropsychological bedside neglect battery that included line-cancellation, letter- and star-cancellation, line-bisection, figure- and shape-copying, and free-drawing tasks (Wilson, Cockburn, & Halligan, 1987). All but 1 of the patients completed 108 and 315 trials in the baseline and uneven conditions, respectively. The remaining patient completed 72 and 225 trials in the baseline and uneven conditions, respectively.

Table 1. *Patient demographics and lesion information*

Patient	Age at time of testing	Gender	Infarct area	Lesion volume (cc)
E.B.	62	Male	Right putamen, mesial temporal structures	32
A.V.	76	Female	Right thalamus, lateral ventricle	53
F.G.	67	Male	Right parietal and frontal structures	110
M.A.	76	Male	Right temporal and frontal structures	61
J.S.	71	Male	Right frontal, parietal, and parieto-temporo-occipital structures	89
J.M.	56	Male	Right frontal and temporal structures	126
R.B.	67	Male	Right inferior parietal structures	90

Results

Less than 1% of the data was excluded because of incorrect response, and 5% of the correct data was excluded for being more than 2 *SD*s from the condition mean. The fact that accuracy was high was not surprising given that the patients knew that a target was present on every trial; therefore, we present only the RT data.

As before, a Probability (baseline, uneven) × Column (1–6) repeated measures ANOVA was conducted (see Fig. 2, top panel; the bottom panel of Fig. 2 includes data for the elderly participants in Experiment 1 for purposes of comparison). The critical finding was the presence of a significant interaction between these two variables, $F(5, 30) = 2.61, p < .05$. Pair-wise comparisons of corresponding columns in the two probability conditions revealed a significant reduction (p always $< .03$) in RT in columns 1 through 3 in the uneven compared with the baseline condition and no significant change in columns 4 through 6 (baseline column mean – uneven column mean was 1,142.71 for column 1; 1,146.46 for column 2; 1,037.71 for column 3; 761.86 for column 4; 374.43 for column 5; and −196.6 for column 6).

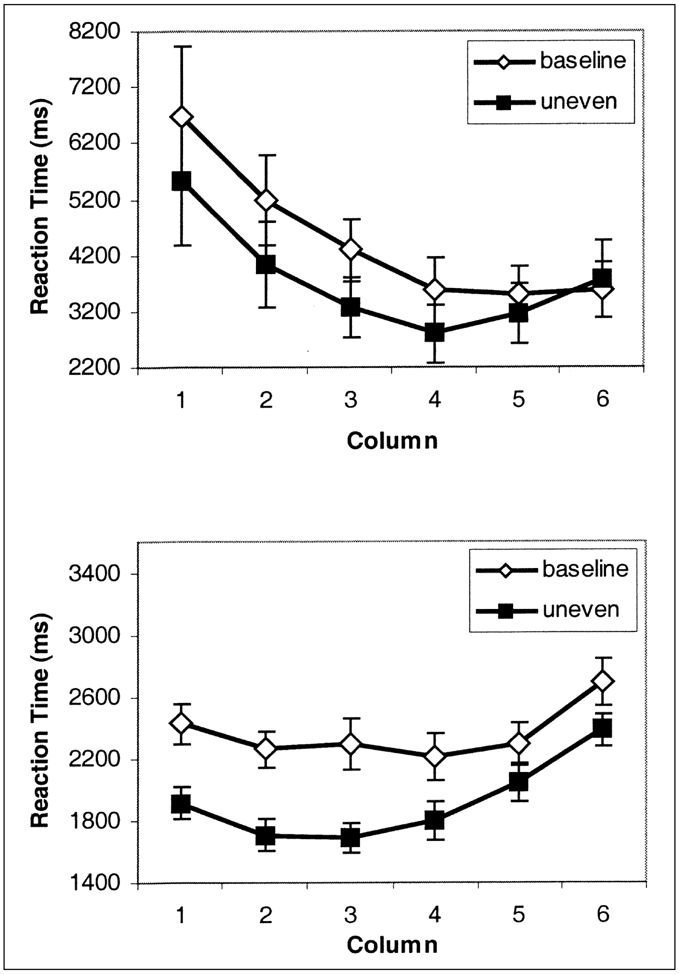

Fig. 2. Mean reaction time as a function of the target's column location in neglect patients (top panel; Experiment 2) and elderly control participants (bottom panel; Experiment 1). Results are shown separately for the baseline and uneven conditions. The data for the elderly are included for comparison. Vertical bars indicate standard error. Note the difference in ordinate-axis scale for the two populations.

We ran separate analyses for each probability condition in order to assess differences for search on the left versus right side of the screen. Results from the baseline condition were consistent with classic symptoms associated with hemispatial neglect: RTs for columns 1 and 2 were significantly slower than RTs for columns 6 and 5, respectively, whereas the mean RT for column 3 was not significantly different from the mean RT for column 4 (difference in column means: column 1 − column 6 = 3,087.03 ms; column 2 − column 5 = 1,658.94 ms; column 3 − column 4 = 735.21 ms). In the uneven condition, discrimination performance was still significantly slower in column 1 than column 6 (although the difference decreased to 1,747.71 ms). However, there were no significant differences between RTs for columns 2 and 5 and for columns 3 and 4 (difference in column means: column 2 − column 5 = 886.92 ms; column 3 − column 4 = 459.35 ms).

The fact that facilitation due to the probability manipulation did not affect all columns to the same extent (i.e., performance in column 1 still differed from performance in column 6 in the uneven condition) indicates that neglect was not eliminated by the statistical manipulation (for a similar finding, see Shalev & Humphreys, 2000). When we analyzed RTs from the left-side columns (1–3) in the two conditions, we found only significant main effects of condition, $F(1, 6) = 15.98$, $p < .01$, and column, $F(2, 12) = 26.72$, $p < .01$. Performance was faster in the uneven than in the baseline condition and in columns that were closer to starting fixation than in columns that were further away. However, there was no interaction, $F(2, 12) = 0.76, p > .1$, indicating that there was an equivalent degree of facilitation across all left-side columns. The fact that the slope of the attentional gradient remained unaffected by the contingencies and that the facilitation afforded by the statistical regularity was additive suggests that the source of the facilitation observed lies outside of what is traditionally considered to be the visuospatial attentional system (e.g., parietal lobe and frontal eye fields; Corbetta et al., 1998; Mesulam, 1999).

In order to assess whether the effect of statistical cuing might be qualitatively different for elderly and patient populations, we calculated difference ratios between the two probability conditions in the six columns for patient and elderly participants, using the formula ([baseline column mean – uneven column mean] / [baseline column mean + uneven column mean]) * 100. Most notably, the Population (elderly, patient) × Column interaction was not significant, $F(5, 70) = 1.40$, $p > .1$ (Fig. 3). This result indicates that the change in performance between the baseline and uneven conditions as a consequence of the contingency in target location was equivalent in elderly and patient participants.

Interestingly, none of the patients reported having noticed the probability distribution during the experiment, suggesting that, as in Experiment 1, the results are not a consequence of explicit strategy formation.

In sum, our data demonstrate that neglect patients show an additive sensitivity to statistical contingencies governing the distribution of targets in the visual field, that their behavior is modulated without explicit knowledge, and that their relative decrease in RT between conditions is equivalent to that seen in elderly participants.

DISCUSSION

The two experiments reported here investigated the ability of participants to exploit probability cues related to target locations within a visual search display. These results provide an important demonstra-

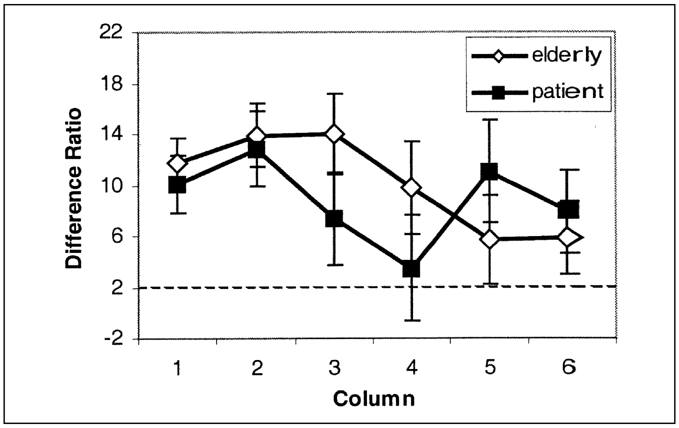

Fig. 3. Mean difference ratio as a function of the target's column location, for neglect patients and elderly participants. Difference ratios were computed by the following formula: ([baseline column mean − uneven column mean] / [baseline column mean + uneven column mean]) * 100. Vertical bars indicate standard error.

tion of how the visual attention system may adapt to environmental statistics reflexively in order to maximize the efficiency of behavioral output. Moreover, they demonstrate that behavioral adaptability may precede explicit knowledge of environmental properties and that separable systems may subserve attentional orienting and probability matching.

Experiment 1, conducted with normal young and elderly participants, revealed that a discrimination judgment was facilitated when targets appeared within the more probable region of space. Furthermore, this facilitation occurred without the individuals' explicit knowledge of differences in the likelihood of target location. Experiment 2 extended these results by showing that implicit sensitivity to target location probabilities is present in patients with hemispatial neglect even when the target appears in the neglected region. Although neglect is not eliminated, significant facilitation in target discrimination does occur. Interestingly, the sensitivity to the statistical contingencies was equivalent in magnitude to that of elderly control participants and largely additive. That patients with an attentional deficit are able to exploit the contingencies in target location to the same extent as normal individuals without the attentional gradient being qualitatively altered suggests that these processes may be dissociable.

Two important issues arise from these findings, and we deal with each in turn. The first issue concerns a possible neural mechanism that mediates the significant facilitation by target location probabilities. At least three possibilities exist: The facilitation may occur during the perceptual encoding of the input, during the sensorimotor transformation between the visual input and motor response, or during the planning or execution of the response.

The results from Experiment 2 render the second possibility unlikely, as the effect of the uneven cuing did not alter the attentional gradient of patients per se. Furthermore, because neglect is often thought of as resulting from damage to regions of the brain that implement sensorimotor transformations (Andersen, Snyder, Bradley, & Xing, 1997; Behrmann, Ghiselli-Crippa, Sweeney, Di Matteo, & Kass, 2002), it is likely that the facilitation observed in patients occurs in encoding or response processes. This is not to say, however, that the sensorimotor mechanisms involved in attentional orientation are insensitive to the statistical contingencies that lead to probability matching (Platt & Glimcher, 1999), but only that these mechanisms are unlikely to be requisite. Although our remaining discussion is primarily limited to structures that lie at extreme ends of the processing stream, we recognize that many systems may be modulated by behaviorally relevant stimulus regularities. In particular, many studies have found prefrontal cortex and basal ganglia structures to be involved in decision making, reward, and spatial sequence learning (Bischoff-Grethe, Martin, Mao, & Berns, 2001; Breiter, Aharon, Kahneman, Dale, & Shizgal, 2001; Pratt & Mizumori, 2001).

We now examine two explanations involving early sensory and late motor structures that could plausibly be modulated by experimental contingencies such as the one we employed. The notion that the uptake of the target information is facilitated by the contingencies is consistent with the finding that early event-related potential components such as lateral occipital P1 and N1 are larger for targets appearing in expected than in unexpected locations (Handy, Green, Klein, & Mangun, 2001). It is also in agreement with functional magnetic resonance imaging evidence that top-down attentional effects can selectively enhance V1 activation, with concomitant suppression in surrounding regions; selective enhancement may act to reduce competition when multiple stimuli are present (Fink, Driver, Rorden, Baldeweg, & Dolan, 2000; Sengpiel & Huebener, 1999). These results suggest that attentional expectancies in this experiment (although implicit) may have provided feedback to early visual areas to enhance processing of objects located in the more probable region.

Although the proposal that the contingencies affect enhanced perceptual processing is compelling, it is also possible that the contingencies facilitate subjects' responses, in the present case, the saccadic eye movements that are necessary for target discrimination. The facilitation in target discrimination may arise because neurons involved in coding saccadic eye movements to the more probable side of space are primed. For example, Basso and Wurtz (1998) recorded from buildup neurons in the superior colliculus of monkeys performing a saccadic eye movement task. They found greater activation during the delay period prior to target selection when the target always appeared in the same location than when it appeared in different locations. These findings suggest that presaccadic activation is modulated by increased probability of the target location. Interestingly, the activity of buildup neurons in the intermediate layer of the superior colliculus is sensitive to covert shifts of attention even when no eye movements are made (Kustov & Robinson, 1996). Consistent with this finding, preliminary data from our lab using a similar task that precludes eye movements show the same facilitation effects in response to statistical contingencies in target location.

Either or both of these neural mechanisms would be consistent with our findings, but the second important issue that arises—why the mechanism employed is implicit rather than strategic—may be better understood at a behavioral level. Subjects were not overtly aware of the underlying contingencies despite their ability to exploit them. One possible explanation of this fact is that the paradigm we adopted did not require explicit awareness of the target location. Because the statistical contingencies were orthogonal to the feature of search (i.e., letter identity), subjects did not necessarily develop an awareness of the contingencies. A second, perhaps more interesting possibility is that the particular paradigm is not responsible for the fact that the processing was implicit and that, instead, the mechanism whereby the contingencies are instantiated operates without explicit tracking of the contingencies.

Wolfe and his colleagues (Wolfe, Alvarez, & Horowitz, 2000; but see Peterson, Kramer, Wang, Irwin, & McCarley, 2001) showed that when all items in a visual search display are equivalent in salience, attention is deployed at random. One explanation they gave is that eye movements and attention move rapidly, whereas volitional delegation of attention to a specific location is much slower. Thus, it is less costly to make rapid, random movements than to make fewer, deliberate movements. In the paradigm we employed, the saccade program that is likely to "win" the competition is one that has historically produced successful target localization; learning may be implicit because reflexive saccade generation is faster than volitional saccade generation. Whether the biasing occurs at the output level, early sensory level, or both is a question that requires further investigation. What is clear is that sensitivity to the statistics of the environment can lead to additive response facilitation in adult participants, even when there is no explicit awareness of the contingency. Interestingly, this is true even for individuals with orienting deficits resulting from damage to areas of the attentional network.

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