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Why rare targets are slow: Evidence that the target probability effect has an attentional locus

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Abstract Target probability has a well-known effect on detection times: Targets that occur with lower probability are detected more slowly than their higher-probability counterparts. A long-standing issue of interest is what causes this effect. In the two experiments of this study, we examined the possibility that the target probability effect has an attentional locus. We report two key findings that are consistent with this hypothesis. First, we observed a magnification of the effect when the attentional resources available for target detection were limited. Second, we also observed the complementary pattern: an attenuation of the effect when more attentional resources were available for detection. We propose that the target probability effect is caused by an asymmetry in the attentional demands made by targets that occur with different probabilities, with low-probability targets being more attentionally demanding than high-probability ones.

Keywords Attention · Target Detection · Target Probability

Introduction

It is well-known that target probability has a strong influence on behavior. For example, recent studies utilizing the visual search paradigm have demonstrated that infrequently appearing target stimuli are more likely to be missed than their more frequently occurring counterparts (Wolfe et al., 2007). However, it is also true that, even in situations in which accuracy is perfect or close to perfect, target probability has a pronounced effect on detection times. For example, in the simple detection paradigm, in which stimuli are presented one at a time and detection accuracy is extremely high, the standard observation is that infrequently occurring targets are detected more slowly than more frequently occurring ones (Laberge & Tweedy, 1964; Miller & Pachella, 1973). This effect of target probability on response times (RTs), especially when accuracy is very high, is of central interest to this report. Accordingly, in the present study, we utilized the detection paradigm described above.

Much of the behavioral research on the target probability effect (TPe) has focused on isolating its locus. Various proposals have implicated peripheral operations, such as perceptual- and response-level processing in the TPe. For example, one idea is that the TPe is caused by a perceptual advantage enjoyed specifically by higher-probability targets (Biederman & Zachary, 1970; Dykes & Pascal, 1981; Lau & Huang, 2010; Menneer, Donnelly, Godwin, & Cave, 2010; Orenstein, 1970). An alternative proposal is that the TPe is caused by differences in the levels of response preparation associated with high- and low-probability targets, with observers being more prepared to respond to high-probability targets, as these occur more frequently (Gehring, Gratton, Coles, & Donchin, 1992; Hawkins, Mackay, Holley, Friedin, & Cohen, 1973).[1]

Apart from behavioral studies, the manipulation of target probability has also been a mainstay of neuroscience research. In contrast to behavioral studies, the effect of target probability in neuroscientific investigations is not typically discussed with respect to peripheral processing areas of the brain. Rather, its effect is commonly discussed in relation to prefrontal and parietal regions. In both fMRI and ERP investigations, an inverse relationship is typically observed between target probability and neural activity, with lower-

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[1] The response preparation view is best suited to situations in which the different probability targets have different responses or when target probability is blocked. It has difficulty, however, accounting for situations in which the different probability targets share the same response and are presented within the same block.

probability targets producing greater frontoparietal activation than higher-probability targets (Casey et al., 2001; Duncan-Johnson & Donchin, 1977; Hon, Ong, Tan, & Yang, 2012; Huettel, Mack, & McCarthy, 2002; Tueting, Sutton, & Zubin, 1970). The prevalent view is that frontoparietal regions encode the currently relevant task context (Corbetta & Shulman, 2002; Desimone & Duncan, 1995; Miller & Cohen, 2001). Within this framework, the effect of target probability is discussed in terms of representational update. The appearance of a task-relevant stimulus, such as a target, precipitates an updating of frontoparietal task representations (Donchin & Coles, 1988). According to this view, targets that occur with lower probability produce greater adjustments to task representations because they are more unexpected.

These same frontoparietal regions are also of interest here because they are implicated in attentional control. Sustained activity has been observed in frontoparietal regions throughout periods in which attention is voluntarily deployed (Kastner, Pinsk, De Weerd, Desimone, & Ungerleider, 1999). Furthermore, frontoparietal activity has been observed to increase as attentional demands increase (Culham, Cavanagh, & Kanwisher, 2001; Hon, Epstein, Owen, & Duncan, 2006). Attentional control is said to be exerted when the frontoparietal task representations discussed above influence, via descending (or "top-down") biasing signals, activity in other, related brain systems, such that overall processing converges on what is relevant or attended to (Bressler, Tang, Sylvester, Shulman, & Corbetta, 2008; Kastner et al., 1999; Kastner & Ungerleider, 2000).

The upshot of the preceding discussion is the possibility that the TPe may have an attentional locus. Here, in two experiments, we manipulated the amount of attentional resources available for detection and examined the effect of such manipulations on the TPe.

Experiment 1

In Experiment 1, we assessed the effect of limiting the amount of attentional resources available for detection. Specifically, we assessed the TPe when participants performed a detection task on its own or in conjunction with another attentionally demanding but orthogonal task. Because of the need to share general attentional resources, two attentionally demanding tasks, even if they are very different in nature, can interfere with each other (Bourke, Duncan, & Nimmo-Smith, 1996). Accordingly, we reasoned that, if the TPe has an attentional locus, then limiting the attentional resources available for target detection (by requiring them to be shared with a concurrent task) should magnify the effect.

Method

Participants A group of 24 students from the undergraduate population of the National University of Singapore participated in this experiment. All participants had corrected or corrected-to-normal vision.

Stimuli Letter stimuli were used in both experiments. These were presented on a 24-in. LCD monitor controlled by a PC running the E-Prime software. Each letter stimulus subtended approximately 1.4º of visual angle both vertically and horizontally when viewed from a distance of 50 cm. All stimuli were presented in the center of the screen.

Procedure The participants observed two blocks of serially presented single-letter stimuli. Each block comprised 200 trials. In each block, participants attempted to detect the occurrences of two letters that were designated as targets for that block. Targets accounted for 50 % of all trials within a block. Critically, though, one member of each block's two-item target set occurred more often than the other. Specifically, one target letter was presented on 10 % of all trials within the block (low-probability target), while the other was presented on 40 % (high-probability target). Distractors accounted for the remaining 50 % of trials in a block. When the stimulus was a distractor letter, it was presented for 1,000 ms, followed by a blank frame presented for 1,000 ms and, subsequently, by the presentation of the next stimulus. Target letters, on the other hand, remained onscreen until a response was made. The offset of the target was followed by a 1,000-ms blank frame, and then by the presentation of the next letter. Participants pressed the "/" button with the index finger of their dominant hand to indicate detection of a target. The same response was made to all targets. This reduced the likelihood that any effects of probability would be due to response-level processes. The letters designated as targets in either block were never included in the distractor set, and trial order in each block was randomized for each participant. The participants were not informed of the stimulus probabilities beforehand.

As mentioned earlier, participants performed two blocks of target detection. In one block, designated the *dual-task* block, participants performed the detection task in conjunction with an additional counting task in which they were required to mentally count the number of stimuli that appeared. Both targets and distractors were to be included in this mental count. At four points in the block, the target detection task was interrupted, and participants were asked to report the current value of their count. These interruptions occurred after the 70th, 110th, 140th, and 200th trials. Counting was reset to zero after each interruption. As such, the correct responses for each segment were 70, 40, 30, and 60, respectively. The global stimulus probabilities were maintained in each segment. That is, for any given segment, low-probability targets, high-probability targets, and distractors accounted for 10 %, 40 %, and 50 % of the trials within that segment, respectively. In the single-task block, participants simply performed the detection task on its own. To match the structure of the dual-task block, participants were also interrupted four times during this block, although they did not have to do anything during these interruptions. The interruptions occurred at the same points as in the dual-task block. As before, the global stimulus probabilities were maintained in each segment. Block order (single or dual task) was counterbalanced across participants. There was no evidence of order effects, and, consequently, we collapsed over block order for the analyses reported below.

Results

To begin with, the participants had little difficulty with the concurrent counting test, performing it with 99 % accuracy. Participants also performed the primary detection task with a high degree of accuracy (Table 1). This is unsurprising, given that we used singly presented, highly visible stimuli.

We now turn our attention to the critical RT data. These are depicted in Fig. 1. A fully within-subjects 2 (probability: high, low) × 2 (task: single, dual) analysis of variance (ANOVA) performed on the mean correct RTs revealed reliable main effects of task [$F(1, 23) = 8.675, p < .01$] and probability [$F(1, 23) = 77.19, p < .001$]. Of greatest interest to this study was the ordinal interaction that we found between probability and task [$F(1, 23) = 5.02, p < .05$], indicating that performance to the low-probability targets was disproportionately impaired, relative to their high-probability counterparts.

On the surface, the detection task that we used appears similar to the monitoring one typically adopted in investigations of the vigilance decrement, a time-based effect in which performance is worse at the later stages of an experiment (Davies & Parasuraman, 1982). Could our results simply reflect a difficulty in maintaining vigilance throughout the experiment? We tested this by recasting our data to include stage of experiment as a variable. Recall that, in order to facilitate our counting task, we partitioned both of our blocks into four contiguous segments (see the Method section above). Thus, any time-based effect should be most apparent in a comparison between the 1st and 4th segments, as these were farthest apart in time. A fully within-subjects 2 (probability: high, low) × 2 (load: high, low) × 2 (segment: 1st, 4th) ANOVA revealed, as before, a reliable two-way interaction between task and probability, $F(1, 23) = 5.32, p < .05$. Critically, though, the three-way interaction was not significant ($F < 1$, n.s.; Fig. 2), suggesting that the effect of task on target probability was essentially equivalent in the earliest and latest stages of the experiment. This is contrary to what would be predicted for a vigilance-type effect.

Table 1 Mean detection accuracies (reflected as percentages correct) from Experiment 1

	Probability	
	High	Low
Dual-task	98.9	98.7
Single-task	99.1	98.7

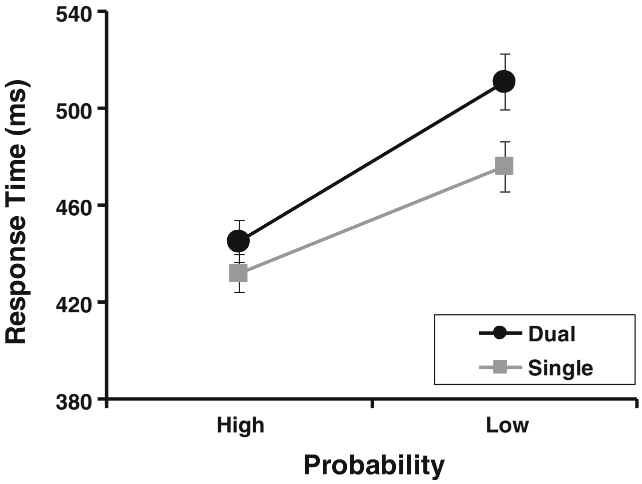

Fig. 1 Mean correct response times to the different probability targets, separated by task (single vs. dual). Error bars indicate 1 *SEM*

Experiment 2

In Experiment 1, we observed that limiting the availability of attentional resources for detection exacerbated the TPe. Here, we examined the converse situation, in which more attentional resources were available for target detection. Specifically, we assessed the TPe when the critical task stimuli "popped out" from irrelevant background elements versus when they did not. We reasoned that less attention would be needed to discern pop-out stimuli, leaving more attentional resources available for the detection of our identity-defined targets. We predicted that the TPe would be attenuated when the critical stimuli were "pop-outs" and required less attention to discern.

Method

Procedure A group of 20 different participants from the same subject pool observed two blocks of serially presented 3 × 3 letter matrices (Fig. 3). Each individual letter subtended approximately 1.4° of visual angle both vertically and horizontally when viewed from a distance of 50 cm. Accordingly, each matrix subtended approximately 4.2° vertically and horizontally. Only the identity of the central letter

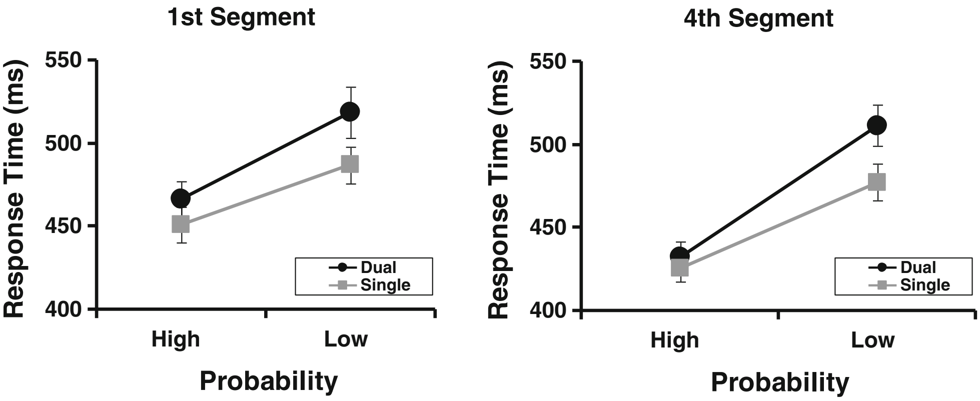

Fig. 2 Effect of task (single vs. dual) on target probabilities at different stages of Experiment 1. Error bars indicate 1 *SEM*

of the matrix changed from trial to trial; the surrounding elements always remained Xs. Participants were instructed to monitor the central letter in order to detect occurrences of either of two predefined targets. As in Experiment 1, one target letter accounted for 10 % of all trials (low-probability target), while the other accounted for 40 % (high-probability target). Distractors accounted for the remaining 50 % of the trials. When the central letter was a distractor, the whole matrix was presented for 1,000 ms, followed by a blank frame presented for 1,000 ms and, subsequently, by the presentation of the next matrix display. When the central letter was a target, the whole matrix remained onscreen until a response was made. The offset of the target display was followed by a 1,000-ms blank frame and then by the presentation of the next stimulus display. The same response ("/" button-press with the index finger) was made to all targets.

Participants performed a 200-trial experimental block. On half of the trials, all letters in the matrix, both the central letter and the surrounding Xs, were presented in blue (Fig. 3, left panel). We refer to these as *standard* trials. On the other half of the trials, the central letter was presented in red, with the surrounding Xs continuing to be presented in blue (Fig. 3, right panel). We refer to these as *pop-out* trials, as the central letter would have "popped out" because it was a feature singleton. Pop-outs and standards contributed equally to the stimulus probabilities (i.e., for low-probability targets, high-probability targets, and distractors) described earlier. Trial order within the block was randomized for each participant.

Fig. 3 Examples of stimuli used in Experiment 2: Standard (left) and pop-out (right) stimuli. In the actual experiment, blue (depicted here as gray) and red (depicted here as black) were used

The experimental block was preceded by a 100-trial training block, which utilized the same stimulus probabilities as the experimental block. Only standard trials (i.e., all-blue displays) were used in the training block. This training block was performed to familiarize participants with the paradigm and, in particular, to establish the all-blue matrices as the standard stimuli of the experiment.

Results

As in Experiment 1, participants in this experiment detected targets with a high level of accuracy (Table 2).

The RT data for this segment are depicted in Fig. 4. A fully within-subjects 2 (probability: high, low) × 2 (stimulus type: standard, pop-out) ANOVA performed on these data revealed reliable main effects of stimulus type [$F(1, 19) = 26.13, p < .001$] and probability [$F(1, 19) = 47.66, p < .001$]. Critically, these effects were qualified by an ordinal, stimulus type x probability interaction [$F(1, 19) = 5.93, p = .025$], indicating that, when the central stimuli "popped out," performance for the low-probability targets was disproportionately improved, relative to their high-probability counterparts.

Discussion

The goal of this study was to test the possibility that the TPe has an attentional locus. We observed two key findings that were consistent with this hypothesis. First, the TPe was

Table 2 Mean detection accuracies (reflected as percentages correct) from Experiment 2

	Probability	
	High	Low
Standard	99.8	99.5
Pop-Out	100	99.0

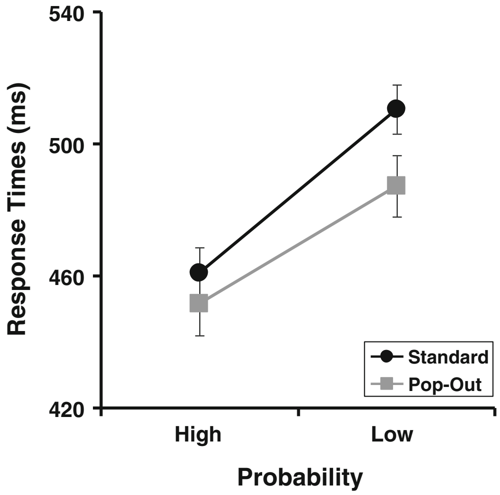

Fig. 4 Mean correct response times to the different probability targets, separated by stimulus types (standard vs. pop-out). Error bars indicate 1 *SEM*

more pronounced when fewer attentional resources were available for target detection. Second, we also observed the complementary pattern: The TPe was attenuated when more attentional resources were available for detection.

The ordinal interactions observed here indicate that the attentional manipulations disproportionately affected the low-probability targets, suggesting that these targets require more attentional processing than do high-probability counterparts to accurately detect. As such, when attentional resources are limited or otherwise engaged, as was the case in our dual-task condition (Exp. 1), detection of low-probability targets is disproportionately impaired. Conversely, when more attentional resources are available for detection, as in the pop-out trials of Experiment 2, performance to the low-probability targets is disproportionately improved.

We can rule out several alternative explanations for our findings. First, as was determined by our subsidiary analysis of Experiment 1, our results are unlikely to stem from difficulties in staying vigilant. Second, our results are unlikely to have been caused by perceptual differences. In Experiment 1, the concurrent counting task did not change perceptual demands, only attentional ones. In Experiment 2, the appearance of a feature singleton, although making it easier to separate the central letter from the surrounding Xs, did not indicate the occurrence of the identity-defined targets. Third, given that all of our targets shared the same response, it is unlikely that our results were produced by simple response preparation differences. Finally, our ordinal interactions are unlikely to have stemmed from simple floor or ceiling effects associated with the high-probability targets. Across participants, the mean standard deviations of the "baseline" high-probability target conditions of the two experiments (i.e., single-task high-probability targets in Exp. 1 and the high-probability standards of Exp. 2) were appropriately large (60 and 52 ms, respectively)—as large, in fact, as the observed TPes. This indicates that there was "room" for performance to vary, in one direction or the other, as a consequence of the attentional manipulations.

Target probability has been found to affect performance to multi-item target sets in different paradigms, including simple detection, as replicated here, and visual search (Godwin et al., 2010; Menneer et al., 2010). The present findings contribute to our understanding of this issue by speaking to the allocation of attentional resources within multi-item target sets. Recall that our low- and high-probability targets were two constituents of the same target set, being searched for simultaneously, and even sharing the same response. One possibility is that attentional resources are deployed on the basis of broad category differences—for example, between targets and distractors as a whole. The implication of such an idea is that all members of the same target set should make similar demands on attention. Here, though, our data suggest that the allocation of attentional resources is much more fine-grained than that, with different members of the same target set being capable of making different demands on attention. Probability of occurrence is likely one of the factors that determine such an asymmetry.

Previous influential work has proposed the idea that probability information is acquired extremely quickly (Estes, 1964) and effortlessly (Hasher & Zacks, 1984), possibly even without the need for conscious monitoring. Our data suggest, though, that its accrual can produce changes to currently held task representations that ultimately result in asymmetries in the amount of attentional control required by the different task-relevant elements.

In summary, we report evidence of a central locus to the TPe: We found that attentional manipulations modulated the TPe, even when perceptual and response considerations were held constant. Nonetheless, the relationship between the attentional locus demonstrated here and the previously forwarded perceptual and response-related ones remains an open and interesting question, especially considering that the establishment and maintenance of task-relevant perceptual templates and action plans rely on top-down attentional contributions (Corbetta & Shulman, 2002; Desimone & Duncan, 1995; Miller & Cohen, 2001). It is worth mentioning, though, that our results implicate a different target type than do typical perceptual and response preparation accounts, which posit that the TPe hinges on advantages enjoyed by the high-probability targets (see the Introduction). In contrast, our data point to the low-probability targets as being central to the effect. Further research will be required to provide a definitive statement on this issue.

References

Biederman, I., & Zachary, R. A. (1970). Stimulus versus response probability effects in choice reaction time. *Perception & Psychophysics, 7,* 189–192. doi:10.3758/BF03208655

Bourke, P. A., Duncan, J., & Nimmo-Smith, I. (1996). A general factor involved in dual-task performance decrement. *Quarterly Journal of Experimental Psychology, 49,* 525–545.

Bressler, S. L., Tang, W., Sylvester, C. M., Shulman, G. L., & Corbetta, M. (2008). Top-down control of human visual cortex by frontal and parietal cortex in anticipatory visual spatial attention. *Journal of Neuroscience, 28,* 10056–10061. doi:10.1523/JNEUROSCI.1776-08.2008

Casey, B. J., Forman, S. D., Franzen, P., Berkowitz, A., Braver, T. S., Nystrom, L. E., et al. (2001). Sensitivity of prefrontal cortex to changes in target probability: A functional MRI study. *Human Brain Mapping, 13,* 26–33. doi:10.1002/hbm.1022

Corbetta, M., & Shulman, G. L. (2002). Control of goal-directed and stimulus-driven attention in the brain. *Nature Reviews Neuroscience, 3,* 201–215.

Culham, J. C., Cavanagh, P., & Kanwisher, N. G. (2001). Attention response functions: Characterizing brain areas using fMRI activation during parametric variations of attentional load. *Neuron, 32,* 737–745.

Davies, D. R., & Parasuraman, R. (1982). *The psychology of vigilance*. London, UK: Academic Press.

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neuroscience, 18,* 193–222. doi:10.1146/annurev.ne.18.030195.001205

Donchin, E., & Coles, M. G. H. (1988). Precommentary: Is the P300 component a manifestation of context updating? *The Behavioral and Brain Sciences, 11,* 355–374.

Duncan-Johnson, C. C., & Donchin, E. (1977). On quantifying surprise: The variation of event-related potentials with subjective probability. *Psychophysiology, 14,* 456–467.

Dykes, J. R., & Pascal, V. (1981). The effects of stimulus probability on the perceptual processing of letters. *Journal of Experimental Psychology. Human Perception and Performance, 7,* 528–537.

Estes, W. K. (1964). A detection method and probabilistic models for assessing information processing from brief visual displays. *Science, 144,* 562. doi:10.1126/science.144.3618.562-a

Gehring, W. J., Gratton, G., Coles, M. G., & Donchin, E. (1992). Probability effects on stimulus evaluation and response processes. *Journal of Experimental Psychology. Human Perception and Performance, 18,* 198–216. doi:10.1037/0096-1523.18.1.198

Godwin, H. J., Menneer, T., Cave, K. R., Helman, S., Way, R. L., & Donnelly, N. (2010). The impact of relative prevalence on dual-target search for threat items from airport X-ray screening. *Acta Psychologica, 134,* 79–84.

Hasher, L., & Zacks, R. T. (1984). Automatic processing of fundamental information: The case of frequency of occurrence. *American Psychologist, 39,* 1372–1388.

Hawkins, H. L., Mackay, S. L., Holley, S. I., Friedin, B. D., & Cohen, S. L. (1973). Locus of the relative frequency effect in choice reaction time. *Journal of Experimental Psychology, 4,* 11–26.

Hon, N., Epstein, R. A., Owen, A. M., & Duncan, J. (2006). Frontoparietal activity with minimal decision and control. *Journal of Neuroscience, 26,* 9805–9809.

Hon, N., Ong, J., Tan, R., & Yang, T. H. (2012). Different types of target probability have different prefrontal consequences. *NeuroImage, 59,* 655–662.

Huettel, S. A., Mack, P. B., & McCarthy, G. (2002). Perceiving patterns in random series: Dynamic processing of sequence in prefrontal cortex. *Nature Neuroscience, 5,* 485–490.

Kastner, S., Pinsk, M. A., De Weerd, P., Desimone, R., & Ungerleider, L. G. (1999). Increased activity in human visual cortex during directed attention in the absence of visual stimulation. *Neuron, 22,* 751–761.

Kastner, S., & Ungerleider, L. G. (2000). Mechanisms of visual attention in the human cortex. *Annual Review of Neuroscience, 23,* 315–341. doi:10.1146/annurev.neuro.23.1.315

Laberge, D., & Tweedy, J. R. (1964). Presentation probability and choice time. *Journal of Experimental Psychology, 68,* 477–481.

Lau, J. S., & Huang, L. (2010). The prevalence effect is determined by past experience, not future prospects. *Vision Research, 50,* 1469–1474.

Menneer, T., Donnelly, N., Godwin, H. J., & Cave, K. R. (2010). High or low target prevalence increases the dual-target cost in visual search. *Journal of Experimental Psychology. Applied, 16,* 133–144.

Miller, E. K., & Cohen, J. D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience, 24,* 167–202. doi:10.1146/annurev.neuro.24.1.167

Miller, J. O., & Pachella, R. G. (1973). Locus of the stimulus probability effect. *Journal of Experimental Psychology, 101,* 227–231.

Orenstein, H. B. (1970). Reaction time as a function of perceptual bias, response bias, and stimulus discriminability. *Journal of Experimental Psychology, 86,* 38–42.

Tueting, P., Sutton, S., & Zubin, J. (1970). Quantitative evoked potential correlates of the probability of events. *Psychophysiology, 7,* 385–394.

Wolfe, J. M., Horowitz, T. S., Van Wert, M. J., Kenner, N. M., Place, S. S., & Kibbi, N. (2007). Low target prevalence is a stubborn source of errors in visual search tasks. *Journal of Experimental Psychology. General, 136,* 623–638. doi:10.1037/0096-3445.136.4.623