Visual Information Processing From Multiple Displays

James C. Johnston, Eric Ruthruff and Mei-Ching Lien

Human Factors: The Journal of the Human Factors and Ergonomics Society published online 4 August 2014

DOI: 10.1177/0018720814545974

Visual Information Processing From Multiple Displays

James C. Johnston, NASA Ames Research Center, Moffett Field, California,
Eric Ruthruff, University of New Mexico, Albuquerque, and **Mei-Ching Lien**,
Oregon State University, Corvallis

Objective: In this study, we examined how effectively people can monitor new stimuli on a peripheral display while carrying out judgments on an adjacent central display.

Background: Improved situation awareness is critical for improved operator performance in aviation and many other domains. Given the limited extent of foveal processing, acquiring additional information from peripheral vision offers high potential gains.

Method: Participants carried out a sequence of central perceptual judgments while simultaneously monitoring the periphery for new stimuli. Peripheral detection was measured as a function of central-judgment difficulty, the relative timing of the two tasks, and peripheral event rate.

Results: Participants accurately detected and located peripheral targets, even at the highest eccentricity explored here (~30°). Peripheral detection was not reduced by increased central-task difficulty but was reduced when peripheral targets arrived later in the processing of central stimuli and when peripheral events were relatively rare.

Conclusion: Under favorable conditions—high-contrast stimuli and high event rate—people can successfully monitor peripheral displays for new events while carrying out an unrelated continuous task on an adjacent display.

Application: In many fields, such as aviation, existing displays were designed with low-contrast stimuli that provide little opportunity for peripheral vision. With appropriate redesign, operators might successfully monitor multiple displays over a large visual field. Designers need to be aware of nonvisual factors, such as low event rate and relative event timing, that can lead to failures to detect peripheral stimuli.

Keywords: peripheral detection, aviation, attention, dual task, situation awareness, monitoring, vigilance

---

Address correspondence to James C. Johnston, NASA Ames Research Center, MS 262-4, Moffett Field, CA 94035, USA; e-mail: James.C.Johnston@nasa.gov.

HUMAN FACTORS
Vol. XX, No. X, Month XXXX, pp. 1–22
DOI: 10.1177/0018720814545974

INTRODUCTION

Advances in technology are rapidly increasing both the amount of data available in domains such as aviation and the technical capability to display huge amounts of data to human operators. In contrast, the cognitive architecture of the human operators is essentially fixed, and its information-processing capability is severely limited. The developing mismatch looms as an important problem. How can we arrange for human operators to monitor the vast amount of displayable data without being overwhelmed?

In aviation, situation awareness has been identified as a key to improving pilot performance (Endsley, 2000; Woods & Sarter, 2010). In the past, cockpit situation awareness has mainly been accomplished by sequential scanning of displays designed to be processed in central vision. Major augmentations in cockpit displays are already being tested. The Primary Flight Display is morphing into a Synthetic Vision System (Prinzel, Kramer, Arthur, Bailey, & Comstock, 2005), which will fuse information from multiple sensors and possibly include add-ons for desired path, terrain, weather, and so on. Navigation displays are morphing into Cockpit Situation Displays (Granada, Dao, Wong, Johnson, & Battiste, 2005), which augment standard traffic display with projected paths, 3-D rotation capability, plus added information about terrain and weather.

The challenge to cockpit design is to enhance pilots' ability to acquire what they need from the wealth of information displayed. In part, this requires tailoring each display to facilitate acquisition of needed information. But an additional objective should be to allow pilots processing one display in central vision to simultaneously acquire important additional information from other peripheral displays. The present research tests the extent to which this is possible, examining the case of detection of salient peripheral events. Such events could represent, for instance, a warning message, malfunction indicator, or the appearance of a new plane on radar. Our goal is to better characterize the human performance envelope for peripheral detection, including both capabilities and vulnerabilities. Previous research supplies a few clues, but under a limited set of circumstances. It is an open question to what extent those results generalize to the wider range of conditions of interest in applied settings, including not only the cockpit but air traffic control facilities, space mission vehicles, and even automobiles.

Basic research on attention capture has established that, under appropriate circumstances, certain stimuli can rapidly and involuntarily capture attention. Current debate concerns the extent to which attention capture is primarily driven "bottom up" by salient stimulus properties (e.g., moving, flashing, unique, or abrupt-onset stimuli) or "top down" by cognitive filtering based on current task goals. Following Posner's (1980) conceptualization of attention capture as "exogenous," early studies argued for the bottom-up view (e.g., Theeuwes, 1994; Yantis, 1993; Yantis & Jonides, 1984). This conclusion was later challenged by Folk, Remington, and Johnston (1992), who found that stimuli high in inherent salience (abrupt onsets) could not capture attention unless observers had a reason to actively look for them. They also found that stimuli low in inherent salience could nevertheless strongly capture attention if they had properties the viewer was looking for (e.g., a red dot can capture attention if the target is a red letter). Folk et al. therefore proposed that involuntary attentional capture is contingent on a match between the properties of a stimulus and the current top-down attentional control settings (see also Lien, Ruthruff, Goodin, & Remington, 2008; Lien, Ruthruff, & Johnston, 2010).

This paper examines circumstances in which peripheral stimuli are both task relevant and salient, seemingly a highly favorable combination for attention capture. However, the current applied context offers several additional challenges. Most attention-capture studies have used stimuli located within a few degrees of fixation, whereas in the applied context, stimuli often appear much further into the periphery. The psychophysical literature indicates that abrupt-onset stimuli can be detected with high accuracy out well past 30° of visual angle (e.g., Rinalducci, Lassiter, MacArthur, Piersal, & Mitchell, 1989; Rinalducci & Rose, 1986), but those studies typically presented stimuli on a very dark, continuous background with extremely high contrast. Under the less favorable conditions of our experiments (and a broad range of applied real-world situations), stimuli appear at only moderate contrast against a relatively bright, heterogeneous background.

Furthermore, attention-capture experiments typically involve only a single task, whereas our paradigm inherently requires multitasking—operators must monitor for peripheral events while carrying out another cognitive task in foveal vision. Multitasking imposes an additional set of obstacles, including the putative central bottleneck (Lien, Ruthruff, & Johnston, 2006; Pashler & Johnston, 1989). The electrophysiological research of Brisson and Jolicoeur (2007) showed that performance of one discrete task can delay attention capture by other stimuli for several hundred milliseconds (see also Lien, Croswaite, & Ruthruff, 2011). In the present study, use of a nearly continuous primary task rather than a discrete one might not merely delay an attentional shift but block it from ever occurring.

In summary, the operational context considered in this study involves numerous additional hurdles not encountered in classic attention-capture studies, including peripheral presentation against heterogeneous backgrounds, the diversion of spatial attention to foveal objects, and the loss of central cognitive resources to decision making on the primary foveal task. Such obstacles are common to a wide variety of real-world domains, so it is important to investigate their consequences.

A few recent applied studies have incorporated many of the sources of difficulty just described. Sarter and colleagues (Hameed, Ferris, Jayaraman, & Sarter, 2009; Nikolic, Orr, & Sarter, 2004) have studied the applied problem of enabling operators to monitor for peripheral warning messages while working on another central display. Operators had a high rate of success responding to peripheral targets, provided that the displays had high visual contrast (unlike many existing displays, such as the flight-computer mode indicator).

Peripheral detection was, however, impaired when peripheral displays contained irrelevant background stimuli with visual properties similar to the target peripheral stimuli.

In the present study, we explored several additional potential vulnerabilities. The first is the difficulty of the central task: A more demanding central task might require additional cognitive processing resources, leaving fewer resources available for peripheral detection. The second is the stage or phase of central-task processing underway when a peripheral target arrives; since different stages are likely to require different mental resources, there could be important fluctuations in the resources available for detecting peripheral targets. The third is low peripheral event rate, which might diminish top-down goal support for detection. In the following sections, we review previous evidence bearing on these potential vulnerabilities.

Central-Task Difficulty

Dual-task studies typically show that as the primary task becomes more difficult, the secondary task suffers more interference (e.g., Pashler & Johnston, 1989). One might naturally expect that in our paradigm, central-task difficulty would have a similar effect. Operators might commit more mental resources to more difficult central tasks, leaving fewer attentional resources available for detecting peripheral events. Consistent with this hypothesis, Lien et al. (2011) reported evidence that a difficult primary task delayed capture by color-defined stimuli (red vs. green). However, in an applied context, it is not clear whether a delay would lead to actual “misses” of target stimuli. It is also unclear whether the delay would occur for more salient stimuli, such as an abrupt-onset plane icon, that need only be detected, not identified. Nikolic et al. (2004) found no additional decrement in detecting a peripheral warning signal when operators performed a more difficult version of *Tetris* as the central task. This surprising finding must be considered tentative, however, since it is a null finding and only for one particular central task. Furthermore, Nikolic et al. did not report data on the extent to which the *Tetris* manipulation actually increased *Tetris* difficulty.

Relative Timing of Peripheral Targets and Central Targets

In the present study, we also addressed the role of temporal overlap between mental events in the central and peripheral tasks. In Nikolic et al. (2004), each peripheral warning message was displayed for 10 s, so participants might have been able to process them during moments of relative inactivity on the *Tetris* task. Also, it is impossible to determine which subphases of *Tetris* task activity impaired detection the most. A definitive assessment of the impact of central-task difficulty requires use of short-duration peripheral stimuli temporally aligned with mental activity on the central task.

Our paradigm displays peripheral plane icons briefly (typically 100 ms), timed to occur 400 ms or 600 ms after the onsets of central-task stimuli. This timing virtually guaranteed that the events would occur while participants were engaged in the central task (which takes about 900 ms). The use of two different stimulus onset asynchronies (SOAs) gave us two chances to find moments during central-task processing in which peripheral targets are missed. At the 400-ms SOA, peripheral targets would most likely arrive during perceptual processing (e.g., extracting plane trajectories), whereas at the 600-ms SOA, they would most likely arrive during later stages, such as making conflict decisions, selecting responses, or executing responses.

Low Event Rate

Does peripheral detection decline when peripheral events are rare, as in many applied aviation situations? It is plausible that the goal of looking for peripheral events has a cognitive strength that decays over time but is replenished with each detection of a peripheral event. Since rare peripheral events necessarily occur with longer average delays, the resulting lower average goal strength could impair detection accuracy.

This issue was not addressed by Nikolic et al. (2004). However, evidence for the importance of top-down task goals with other tasks, such as visual search, is suggestive. Wolfe, Horowitz, and Kenner (2005) reported that very low event rates dramatically reduced the likelihood of detecting a visually obscured target belonging to a prespecified object class (tools). However, it is difficult to extrapolate from the Wolfe et al. paradigm, because it was both easier than our paradigm in some respects and harder in others. On the one hand, for Wolfe et al., the search task was the only task to be performed, whereas we investigate peripheral detection as a secondary task during an ongoing central task. On the other hand, Wolfe et al. employed a variable set of difficult-to-find visual targets, whereas we employed a single, salient, high-contrast stimulus (an abruptly appearing plane icon). Because our peripheral stimuli are so salient, they might announce their presence automatically, even without strongly instantiated top-down goals. In sum, it is highly plausible that in our multitasking paradigm performance might be negatively impacted by low event rate on the peripheral task, but prior research does not provide a definitive answer.

EXPERIMENT 1

In the present study, we examined operators' ability to detect a relevant and salient peripheral stimulus while performing a central task. The central task we used required nearly continuous processing, allowing minimal opportunity to move the eyes or visual attention elsewhere. The peripheral stimulus was displayed very briefly (100 ms) at specific points in time during the central task. Nikolic et al. (2004), in contrast, displayed peripheral warning signals for 10 s. Although prolonged presentation matched the availability of warnings in the applied situation being studied, it allowed considerable opportunity for deliberate scanning to find "peripheral" stimuli using central vision. Thus the Nikolic et al. data do not rule out even the extreme hypothesis that operators are virtually blind to peripheral stimuli during high-workload phases of the central task, succeeding only when workload slackens (and perhaps only by searching the display using central vision). Such a limitation would be important for many operational domains that afford little opportunity for deliberate scanning; in such cases, awareness of brief events in adjacent displays would depend critically on peripheral detection per se.

We simulated a hypothetical future glass cockpit display that eliminates the space separating the Primary Flight Display and the navigation display, merging them into a larger, side-by-side flat-screen image. As shown in Figure 1, the left half of the screen displayed a canonical image of a Synthetic Vision System version of the Primary Flight Display, whereas the right half contained a schematized traffic display. The participants' primary task was to make judgments about whether pairs of planes in the right panel, highlighted in blue, were in conflict (i.e., headed for a collision). We henceforth refer to this primary task as the *central conflict judgment*. While carrying out a sequence of such conflict judgments in central vision, participants also were asked to use peripheral vision to monitor the left-hand display for the occasional entrance of a new plane (not represented in the right-panel display). The peripheral plane image (red and black) was displayed for only 100 ms, too short to allow eye movements but long enough to approach asymptotic perceived brightness (Hurvich & Jamison, 1966). We refer to this task as the *peripheral detection task*.

Each trial consisted of a sequence of four right-panel conflict displays (appearing successively in different quadrants progressing clockwise), followed by a left-panel query about whether and where a red plane had appeared. In Experiment 1, a left-panel red plane appeared on 80% of trials. The SOA between the onset of the conflict pair and onset of the red plane was either 400 or 600 ms. Given mean conflict-task response time (RT) of ~900 ms, the peripheral target typically appeared during processing on the central task.

Method

Participants. Thirty-eight Oregon State University students (typically 18 to 24 years of age, with no previous aviation experience) participated for extra course credit. Given our aim of assessing the impact of the central conflict judgment on peripheral detection, it was necessary to validate that participants were in fact performing this central task. We removed 6 participants with central conflict accuracy below our preset criterion of .8. By removing low-performing participants, we bias our results toward better overall performance on the central task (appropriate for operational contexts, such as aviation, for which a pruning at least as severe typically takes place during operator selection

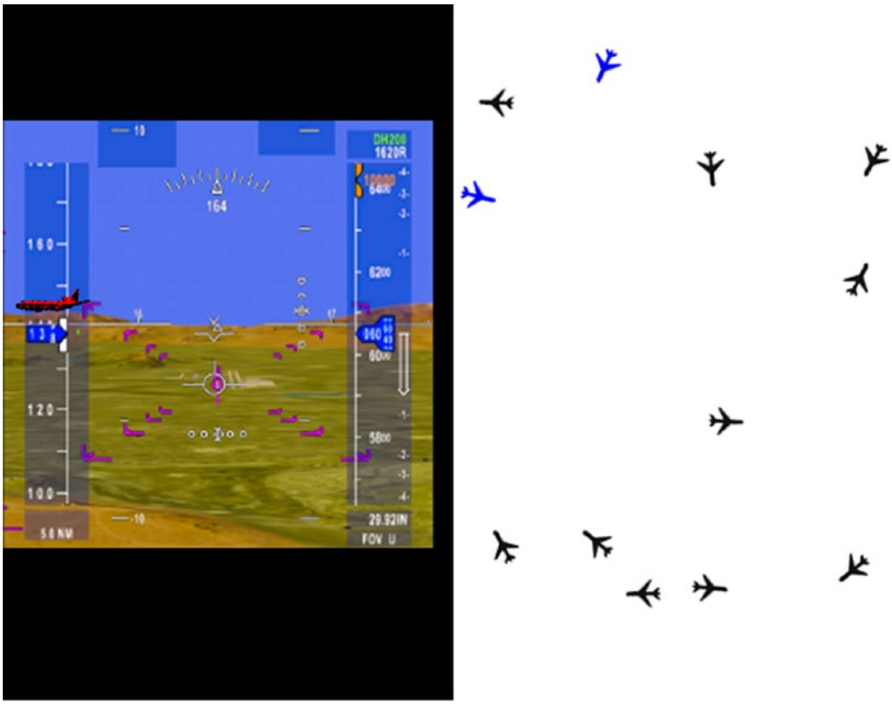

Figure 1. Example of the stimulus display. In this example, a red plane appeared briefly in the leftmost position of the left panel while a conflict judgment was pending in the first quadrant of the right panel. Colored versions of the figures can be downloaded at http://www.unm.edu/~ruthruff/multipledisplays.pdf.

and training). All participants reported normal or corrected-to-normal visual acuity and demonstrated normal color vision using the Ishihara Test.

Apparatus and stimuli. As shown in Figure 1, the display consisted of two adjacent panels. The right panel (19.0° horizontal by 35.4° vertical, at a typical viewing distance of 50 cm) displayed a map of traffic. Next, we characterize the colors using coordinates in CIE color space, an established convention that is device independent and takes into account how humans perceive color (Smith & Guild, 1931). Each display contained 12 black plane icons (1.7° by 1.2°; CIE[Yxy]: 2.69, 0.33, 0.34), 3 in each of the four quadrants, against a white background (CIE[Yxy]: 100, 0.29, 0.31). The left panel (18.3° by 17.5°) displayed a terrain image simulating a possible Synthetic Vision System (light blue sky, CIE[Yxy]: 26.3, 0.19, 0.16; blue vertical bar, CIE[Yxy]: 18.0, 0.17, 0.14; green terrain, CIE[Yxy]: 17.4, 0.42, 0.47; brown terrain, CIE[Yxy]: 19.6, 0.44, 0.41). Occasionally, a plane icon (3.4° by 1.1°) was displayed midway along one of the four edges of this left-panel display (left, right, top, or bottom), 2.0° in from the edge. This plane icon was roughly half red (CIE[Yxy]: 26.2, 0.59, 0.35) and half black (CIE[Yxy]: 2.69, 0.33, 0.34), although we henceforth refer to it simply as the "red plane."

We chose a peripheral plane icon containing both red and black because it ensured that some part of the plane would have high contrast against its background, reducing variance in performance caused by positioning the icon at multiple locations against the heterogeneous background. We calculated color contrasts using ΔE^*_{ab}, a measure of Euclidian distance in an approximately uniform color space—CIE76—where a just noticeable difference (JND) would correspond to a ΔE^*_{ab} of about 2.2 (Wyszecki, 1986). Against the light blue sky, the luminance contrast ($Y_{plane} - Y_{background}$ divided by $Y_{plane} + Y_{background}$) was approximately 0.81 for black and

0.01 for red; the corresponding color contrasts were 89.0 and 134, respectively. Against the green terrain, the luminance contrast was 0.73 for black and 0.20 for red; the color contrasts were 50.8 and 78.5. Against the brown terrain, the luminance contrast was 0.76 for black and 0.14 for red; the color contrasts were 52.8 and 66.0. The luminance contrast between the red and black colors within the plane icon was 81.3, and the color contrast was 100. Luminance and color contrasts were also high in the right panel between the blue plane and the white background (0.94 and 106, respectively).

Design and procedure. On each trial, participants performed a series of four central conflict judgments, one per quadrant (starting with the upper-left quadrant and proceeding clockwise). Trials began with the right panel blank for 500 ms, followed by the display of 12 black planes (3 per quadrant). After another 500 ms, two of the planes in the upper-left quadrant were highlighted by changing from black to blue; the conflict task was undefined until this relevant pair of planes was specified. Participants were instructed to press the *1* key on the numeric keypad if the blue planes were headed for a collision (1/3 of trials) or the *3* key if not headed for a collision (2/3 of trials). Participants were asked to respond accurately and quickly, within a 4-s time-out period. Following incorrect or omitted responses, a low tone sounded for 200 ms; following correct responses, the computer was silent for 200 ms. Next, the previously highlighted plane icons returned to black, and a new pair of planes in the next clockwise quadrant turned blue, revealing the next conflict judgment. Thus there was virtually no free time during the four conflict judgments for eye movements to the peripheral display.

Conflict task difficulty (easy or difficult) was manipulated between blocks. The paths of the nonconflict plane pairs diverged in the easy blocks but converged in the difficult blocks (though never close to colliding). Conflict plane pairs were always headed for an exact collision.

During a trial consisting of four sequential conflict judgments in the right panel (foveal), a red plane sometimes appeared briefly (100 ms) in the left panel (peripheral). The plane appeared on 80% of trials and was absent on the remaining 20% of trials. Planes were equally likely in the left, top, right, and bottom locations. Planes were equally likely to occur during each of the four conflict judgments in a trial. The SOA between the change in color of the conflict-task planes (black to blue) and the onset of the red peripheral plane was either 400 or 600 ms. These conditions (location, time, and SOA) were selected at random on each trial within a block, with replacement (eliminating any possibility of guessing location above chance).

Participants did not respond immediately to the peripheral red plane. Upon completing the four successive conflict judgments in the right panel, a large red question mark appeared in the middle of the left panel. Participants reported seeing a plane by pressing a key on the numeric keypad corresponding to its location (bottom, *2*; left, *4*; right, *6*; top, *8*) and reported not seeing a plane by pressing the *5* key in the middle. This peripheral detection response was unspeeded—there was no time limit, and instructions emphasized accuracy only. For both tasks, participants received an error beep (a low-pitched tone) following an incorrect response.

Participants were given written instructions describing the tasks, along with one example with aircraft headed for a collision and two examples with aircraft not headed for a collision. The experimenter was available to answer questions. Participants were instructed to give priority to the central task (responding as quickly and accurately as possible) while still detecting the presence of peripheral planes to the extent they could. They then performed two practice blocks of 20 conflict judgments, one block each with the easy and difficult conflict geometries. Next they performed 10 experimental blocks of 80 conflict judgments, always alternating between easy and difficult blocks. The order of the easy and difficult blocks was counterbalanced across participants.

Results

Tables 1 and 2 summarize performance on the central conflict judgment and the peripheral detection task. Figures 2 to 3 show the impact of peripheral event rate, central-task difficulty, and SOA on peripheral detection. All analyses of proportional data were performed on arcsine-transformed proportions (Winer, 1962).

TABLE 1: The Impact of Peripheral Event Rate (10% or 80% of trials) on Task Performance in Experiments 1 Through 4

	Central Conflict Judgment		Peripheral Detection		
Event Rate (%)	RT	PC	Hit	FA	Hit(CorLoc)
Experiment 1					
80	935 (22)	.90 (.01)	.94 (.01)	.22 (.06)	.89 (.01)
Experiment 2					
80	960 (24)	.89 (.01)	.92 (.01)	.13 (.03)	.87 (.01)
10	944 (29)	.88 (.01)	.78 (.03)	.03 (.02)	.76 (.03)
Experiment 3					
80	909 (25)	.90 (.01)	.91 (.01)	.05 (.01)	.85 (.02)
10	906 (24)	.91 (.01)	.80 (.03)	.02 (.01)	.77 (.03)
Experiment 4					
80	942 (22)	.88 (.01)	.92 (.01)	.08 (.02)	.89 (.01)
10	909 (21)	.89 (.01)	.80 (.04)	.04 (.01)	.80 (.04)

Note. RT = response time; PC = proportion correct; FA = false-alarm rate; Hit(CorLoc) = probability of detecting the peripheral target and correctly reporting its location. The standard error of the mean is shown in parentheses.

Central conflict judgment. Mean RT for the conflict task was 935 ms, and mean proportion correct (PC) was .90. Analyses of variance (ANOVAs) were conducted on RT and PC as a function of central conflict judgment difficulty (easy vs. difficult). Difficulty affected both RT (easy = 892 ms; difficult = 979 ms), $F(1, 31) = 88.78$, $p < .0001$, $\eta_p^2 = .74$, and PC (easy = .94; difficult = .85), $F(1, 31) = 131.87$, $p < .0001$, $\eta_p^2 = .81$. We clearly succeeded in creating right-panel judgments that differed in difficulty.

Peripheral detection. The mean left-panel detection hit rate was .94 overall, varying little across locations (.94, .95, .95, and .92 for left, top, right, and bottom, respectively). Another important figure of merit is the probability of detection *and* localization: the "Hit(CorLoc)" rate. This measure not only is a good match to what is needed in applied contexts (i.e., location is useful for obtaining further information) but also is much less sensitive to guessing; with four possible locations, the chance guessing rate is only .25. The mean Hit(CorLoc) rate was .89. The fact that this rate approached the overall hit rate (.94) indicates that (a) a very high proportion of hits were genuine target detections and (b) target detection usually also led to localization.

The mean false-alarm rate of .22 was substantial, reflecting the fact that *target present* was the correct answer on 80% of trials. The hit and false-alarm rates can be used to estimate d' and β (sensitivity and bias parameters from signal detection theory; Green & Swets, 1966); however, such estimates are suspect for binary yes/no paradigms because they assume equal variance for the signal and noise distributions. This assumption is unlikely to hold in general and is especially unlikely in the present paradigm. In Experiments 3 and 4, we will confirm this surmise for the present detection task while providing a better paradigm for assessing sensitivity based on six-level confidence ratings.

For the peripheral detection task, we analyzed hit rates, Hit(CorLoc) rates, and false-alarm rates as a function of central conflict judgment difficulty and SOA. Although conflict-task difficulty had a large effect on the central conflict judgment itself, it had surprisingly little effect on peripheral detection; the hit rate was .93 for easy conflict judgments and .95 for difficult ones (see Figure 2), $F(1, 31) = 4.35$, $p < .05$, $\eta_p^2 = .12$, a significant effect opposite to the expected direction. As shown in Figure 3, the hit rate was significantly higher at the 400-ms SOA (.96) than the 600-ms SOA (.92), $F(1, 31) = 18.39$, $p < .001$, $\eta_p^2 = .37$. The interaction between central conflict judgment difficulty and SOA was not significant, $F(1, 31) = 1.35$, $p = .2533$, $\eta_p^2 = .04$.

TABLE 2: The Impact of Central Judgment Difficulty and Stimulus Onset Asynchrony (400 ms vs. 600 ms) on Task Performance in Experiments 1 Through 4

			Peripheral Detection					
	Central Conflict Judgment		Hit		FA		Hit(CorLoc)	
Conflict Difficulty	RT	PC	400	600	400	600	400	600
Experiment 1								
Easy	892 (22)	.94 (.01)	.95 (.01)	.91 (.01)	.21 (.06)	.20 (.06)	.92 (.01)	.86 (.01)
Difficult	979 (24)	.85 (.01)	.96 (.01)	.93 (.01)	.22 (.06)	.23 (.06)	.90 (.01)	.88 (.01)
Experiment 2								
Easy	913 (25)	.93 (.01)	.93 (.01)	.87 (.02)	.05 (.02)	.04 (.02)	.89 (.01)	.81 (.02)
Difficult	992 (23)	.84 (.02)	.93 (.01)	.89 (.02)	.05 (.01)	.05 (.01)	.88 (.02)	.85 (.02)
Experiment 3								
Easy	873 (23)	.94 (.01)	.90 (.01)	.81 (.02)	.06 (.01)	.06 (.01)	.86 (.01)	.82 (.02)
Difficult	941 (23)	.86 (.01)	.90 (.02)	.84 (.02)	.06 (.01)	.05 (.01)	.85 (.02)	.83 (.02)
Experiment 4								
Easy	901 (23)	.94 (.01)	.92 (.01)	.89 (.02)	.04 (.01)	.03 (.01)	.89 (.02)	.87 (.02)
Difficult	949 (19)	.83 (.01)	.91 (.01)	.89 (.02)	.06 (.02)	.05 (.01)	.87 (.02)	.86 (.02)

Note. RT = response time; PC = proportion correct; FA = false-alarm rate; Hit(CorLoc) = probability of detecting the peripheral target and correctly reporting its location. The standard error of the mean is shown in parentheses.

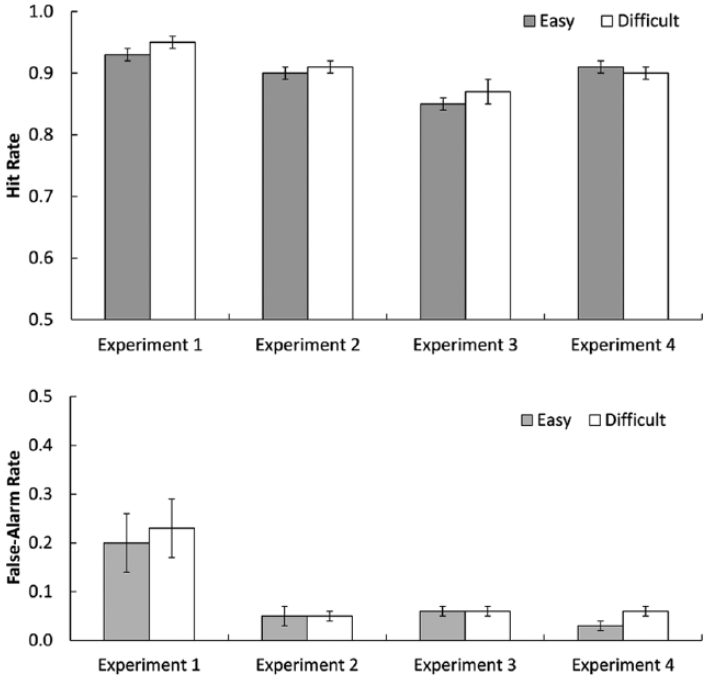

Figure 2. Peripheral detection hit rate and false-alarm rate as a function of the difficulty of the central conflict judgment in Experiments 1 through 4.

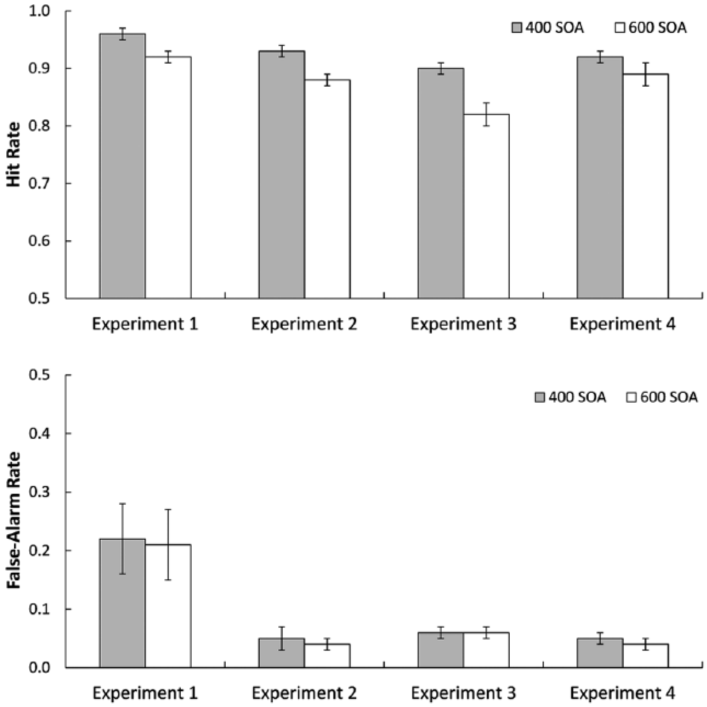

Figure 3. Peripheral detection hit rate and false-alarm rate as a function of stimulus onset asynchrony (SOA) in Experiments 1 through 4.

For the analysis of false-alarm rates, only the main effect of conflict-task difficulty was significant, $F(1, 31) = 4.38$, $p < .05$, $\eta_p^2 = .12$; the false-alarm rate was 0.20 for easy conflict judgments and 0.23 for difficult ones (see Figure 2). The Hit(CorLoc) rate was virtually identical for easy and difficult conflict judgments (.89), $F < 1$, but was significantly higher at the 400-ms SOA (.91) than at the 600-ms SOA (.87), $F(1, 31) = 11.55$, $p < .01$, $\eta_p^2 = .27$ (see Table 2). This SOA effect was larger for easy conflict judgments (.92 vs. 86) than difficult ones (.90 vs. .88), $F(1, 31) = 9.47$, $p < .01$, $\eta_p^2 = .23$.

Discussion

Experiment 1 showed that detection and localization of high-contrast peripheral events (up to 30° of eccentricity) can be highly reliable, even while operators simultaneously perform a demanding task in central vision. Intriguingly, detection accuracy did not decline when the central task was more difficult. It also did not decline for targets further in the periphery; note, however, that the four target locations had different backgrounds. In the General Discussion, we will report a control eccentricity experiment using a homogenous background.

One variable that did impact detection performance was SOA: Detection and localization were impaired at the 600-ms SOA compared to the 400-ms SOA. This finding suggests that there are moments of relative inattention during specific phases of mental processing on another task. Given that mean RT for the central conflict task was 935 ms, a target with a 400-ms SOA would usually have arrived during perceptual processing of the plane trajectories, whereas a target with a 600-ms SOA would usually have arrived at later stages, such as making the conflict judgment, response selection, and perhaps response execution (for participants who responded most rapidly).

Because our main aim was to determine whether peripheral detection is possible during performance of the primary task in central vision, we needed assurance that participants were in fact performing the central task. We therefore excluded participants who did not perform the central task accurately (<.8). Such pruning is appropriate for applied contexts (especially aviation) for which operators typically must demonstrate a high skill level, and weak performers are pruned out. Nevertheless, we conducted a follow-up analysis to determine how much difference the data pruning made. Pooling across experiments, we found that pruning the poor central-task performers increased the peripheral hit rate only from .90 to .91, so any overestimation of the "average" detection rate is modest.

EXPERIMENT 2

In Experiment 1, most participants could reliably detect the peripheral plane and report its location. Note, however, that the peripheral red plane appeared on 80% of trials (20% of conflict judgments). Under real-world conditions, peripheral events can be much rarer. To the degree that peripheral detection benefits from advance preparation (e.g., forming a strong top-down goal to search for that type of object), it might suffer when peripheral events are less expected. On the other hand, it is also plausible that the high salience of our abrupt-onset plane icons would serve as an automatic bottom-up "interrupt" signal for which little or no top-down preparation is required.

To study this issue in Experiment 2, we manipulated event rate. In addition to the original 80% event rate condition from Experiment 1, we also included a new condition with a 10% event rate (manipulated within participants across session halves). Because each trial contained a series of four conflict judgments, the peripheral event now occurred during only 1 out of 40 conflict judgments (2.5%).

Method

Except as noted, the method was identical to that of Experiment 1. Each participant completed two session halves, one each for the low (10%) and high (80%) event rates, with order counterbalanced across participants. Each session half consisted of two practice blocks of 20 trials, then four experimental blocks of 80 trials each.

Participants. Participants were a new batch of 58 Oregon State University undergraduate students. Fourteen were excluded because their central conflict accuracy fell below our criterion of .8.

Results

Central conflict judgment. Mean RT for the conflict task was 953 ms, and mean PC was .88. ANOVAs were conducted on RT and PC as a function of conflict judgment difficulty (easy vs. difficult). The difficulty effect was again statistically significant for RT (easy = 913 ms; difficult = 992 ms), $F(1, 43) = 26.63$, $p < .0001$, $\eta_p^2 = .38$, and for PC (easy = .93; difficult = .84), $F(1, 43) = 68.91$, $p < .0001$, $\eta_p^2 = .62$.

Peripheral detection. The mean hit rate was .91; again, it was little affected by stimulus location (.91, .92, .92, and .89 for left, top, right, and bottom, respectively). The Hit(CorLoc) rate was .86, again only slightly lower than the overall hit rate. The mean false-alarm rate was only .05.

For Experiment 2, it was not possible to analyze all factors in a single ANOVA, due to a reduction in trials per design cell (not only were the data split by session halves, but in the low-event-rate condition, far fewer trials had a peripheral target). Instead, we performed two sets of ANOVAs on hit rates, Hit(CorLoc) rates, and false-alarm rates: (a) with both central-task difficulty and SOA as factors and (b) with event rate as the only factor.

The first set of ANOVAs (pooled across event rates for more stable cell means) assessed the effects of SOA and conflict judgment difficulty on hit rates, Hit(CorLoc) rates, and false-alarm rates. Conflict judgment difficulty again had no effect on peripheral detection rates, $F < 1.0$ (see Figure 2). Hit rates were again higher at the 400-ms SOA (.93) than at the 600-ms SOA (.88), $F(1, 43) = 14.76$, $p < .001$, $\eta_p^2 = .26$ (see Figure 3). The interaction between SOA and conflict judgment difficulty on hit rates was not significant, $F < 1$. No effects on false-alarm rates were significant, Fs < 2.33, ps $> .1343$. For analyses of Hit(CorLoc), there was no effect of difficulty, $F < 1.0$. The Hit(CorLoc) rate was higher at the 400-ms SOA (.89) than at the 600-ms SOA (.83), $F(1, 43) = 15.66$, $p < .001$, $\eta_p^2 = .27$. This SOA effect did not differ significantly for easy (.89 vs. .81) vs. difficult (.88 vs. .85) judgments $F(1, 43) = 3.53$, $p = .0672$, $\eta_p^2 = .08$.

The new ingredient in Experiment 2 was the manipulation of peripheral event rate (80% vs. 10% of trials). As shown in Table 1, lowering the event rate from 80% to 10% substantially reduced the hit rate (.92 vs. .78 for high vs. low event rates, respectively), $F(1, 43) = 40.34$, $p < .0001$, $\eta_p^2 = .48$, but was offset by a substantial decrease in false-alarm rates (.13 to .03), $F(1, 43) = 17.68$, $p < .001$, $\eta_p^2 = .29$. The Hit(CorLoc) rate was also higher at high event rates (.87) than at low event rates (.76), $F(1, 43) = 15.21$, $p < .001$, $\eta_p^2 = .26$.

Discussion

Experiment 2 manipulated event rate. The high rate was 80% of trials and the low rate was 10% of trials. Because each trial had four right-panel conflict judgments, the low event rate amounted to an average of only one peripheral target for every 40 conflict judgments. With low event rate, hit rates declined noticeably from .92 to .78, and Hit(CorLoc) rates declined significantly from .87 to .76.

EXPERIMENT 3

In Experiment 2, low event rate produced not only fewer hits but also fewer false alarms, indicating a more cautious response bias. Note that if the only effect of low event rate were a bias against reporting target detection, then it could conceivably be counteracted by training operators to lower their criterion for rare events. Alternatively, the drop in hit rate might reflect an actual decrease in sensitivity. As noted earlier, with simple binary decision data (e.g., detect vs. no detect), there is a "standard" way to compute d' (a sensitivity measure) for each condition based on just the hit and false-alarm rates. However, the standard calculation requires the questionable assumption that the signal and noise distributions have equal variance. This assumption is rarely plausible: Signal distributions typically have additional variability.

Rather than present misleading sensitivity calculations from binary data, we chose to withhold formal tests of sensitivity and instead to perform an experiment better suited to producing valid sensitivity estimates. Specifically, Experiment 3 replaced the binary yes/no response with a confidence rating, using a six-level scale. This procedure allows us to derive a receiver operating characteristic (ROC) curve and measure sensitivity nonparametrically, without assuming equal variance or even normality (see, e.g., Green & Swets, 1966; Swets, 1986).

Unlike Experiments 1 and 2, we required reports of peripheral plane location on every trial, even following a "plane-absent" report. The revised procedure provides a check on the use of the confidence scale: When participants express very low confidence that a plane was present, location accuracy should also be low. In fact, it was .28, barely above the chance guessing level (.25).

Method

Except as noted, the method was identical to Experiment 2. At the end of each trial, participants gave a peripheral plane confidence rating using the *A, S, D, F, G*, and *H* keys. From left to right, the key assignments ranged from high confidence of plane presence (*A*) to high confidence of plane absence (*H*). These six keys were labeled with three *Y*s and three *N*s, varying in size according to the confidence level (largest size for higher confidence, keys *A* and *H*; smallest size for lower confidence, the middle keys *D* and *F*). Following every confidence response, participants always made a forced-choice response regarding plane location.

Participants. A new sample of 59 Oregon State University undergraduates participated in this experiment. Eleven were excluded because their conflict judgment accuracy fell below .8.

Results

Central conflict judgment. Mean RT for the conflict task was 907 ms and mean PC was .90. ANOVAs again revealed a significant effect of conflict difficulty on conflict RT (easy = 873 ms; difficult = 941 ms), $F(1, 47) = 45.73$, $p < .0001$, $\eta_p^2 = .49$, and PC (easy = .94; difficult = .86), $F(1, 47) = 86.30$, $p < .0001$, $\eta_p^2 = .65$.

Peripheral detection. To extract binary classification results comparable to the previous experiments, we categorized the leftmost three responses (keys labeled *Y*) as "plane present" and the rightmost three responses (keys labeled *N*) as "plane absent". The resulting mean hit rate was .88, with only minor modulation by stimulus location (.89, .91, .89, and .84 for the left, top, right, and bottom locations, respectively). The mean false-alarm rate was .06. The mean Hit(CorLoc) rate was .84, only a smidgeon lower than the .88 overall hit rate.

We first analyzed each of our peripheral-task measures as a function of central-task difficulty and SOA, pooled across event rate, due to the small numbers of trials at low event rates. The results replicated those of the previous experiments. Hit rates were significantly higher at the 400-ms SOA (.90) than at the 600-ms SOA (.82), $F(1, 47) = 15.35$, $p < .001$, $\eta_p^2 = .25$ (see Figure 3). Conflict judgment difficulty did not influence hit rates (easy = .85; difficult = .87), $F < 1$ (see Figure 2). The interaction between conflict judgment difficulty and SOA was not significant, $F < 1.0$. The effects on false-alarm rates were not significant, *F*s < 1.0. For target location analyses, the Hit(CorLoc) rate was not significantly affected by central-task difficulty, $F < 1.0$. There was no significant difference in Hit(CorLoc) between the 400-ms SOA (.86) and the 600-ms SOA (.83), $F(1, 47) = 2.16$, $p = .1486$, $\eta_p^2 = .04$. SOA and difficulty did not interact, $F < 1.0$.

With a second set of ANOVAs, we examined event rate. As shown in Table 1, decreasing the event rate reduced the hit rate from .91 to .80, $F(1, 47) = 18.11$, $p < .0001$, $\eta_p^2 = .28$; false-alarm rates (from .05 to .02), $F(1, 47) = 18.40$, $p < .0001$, $\eta_p^2 = .28$; and Hit(CorLoc) rates (from .85 to .77), $F(1, 47) = 8.38$, $p < .01$, $\eta_p^2 = .15$. False-alarm rates were lower in this experiment (.04) than in Experiment 2 (.08), despite identical event rates. When uncertain about the target, participants forced to make a binary yes/no decision might sometimes guess *yes*, whereas participants allowed to use a confidence rating scale could just give a low-confidence *no* response.

Figure 4 (top panel) shows the ROC curve (pooled across participants) for low event rate (open circles) and high event rate (open squares). Each point reflects the hit rate and false-alarm rate for one of the five possible binary splits of the 6-point confidence rating scale per condition. The ROC curve shows that for any given false-alarm rate, the hit rate was typically greater with high event rate than with low event rates. This pattern suggests a loss of sensitivity to peripheral targets. The ROC curve also shows that low event rate biased responses toward *no*, yielding both fewer hits and fewer false alarms. Also shown are the corresponding low-event-rate data point (filled circle) and the high-event-rate point (filled square) from the yes/no judgment in Experiment 2. These points lie close to the ROC curve from the present experiment, suggesting that the change in procedure (confidence ratings instead of yes/no decisions) had little impact on sensitivity.

To assess changes in sensitivity across event rates more formally, we calculated a nonparametric measure of sensitivity—the area under the ROC curve (AUC)—for each participant in the low-event-rate and high-event-rate conditions. An ANOVA on AUC with the factors of event rate (a within-subject variable) and session order (half of participants received low event rates first, and half received high event rates first) revealed a highly significant decrease in sensitivity for low event rates (AUC = .90) compared to high event rates (AUC = .96), $F(1, 46) = 13.71$, $p < .001$, $\eta_p^2 = .23$. There was no main effect of session order and no interaction between session order and event rate, *F*s < 1.0.

The shape of the ROC curves is also noteworthy. The left-hand, steeply climbing section of the curve has a bowed shape, with each segment incorporating additional information favoring target presence but subject to diminishing returns. The right-hand segments form a straight line approximately collinear with the point (1.0, 1.0), consistent with additional segments incorporating no additional information favoring target presence, reflecting only incrementally greater bias to guess “plane present.”

Discussion

In Experiment 3, we asked participants to rate their confidence that a peripheral target plane was present, using a 6-point scale ranging from *highest-confidence yes* to *highest-confidence no*. A major advantage of this confidence-rating method is that it provides a nonparametric measure of sensitivity, the AUC (Figure 4, top panel). The AUC data show that a substantial lowering of event rate produced a statistically significant drop in sensitivity for detecting peripheral targets. In addition, the ROC curves

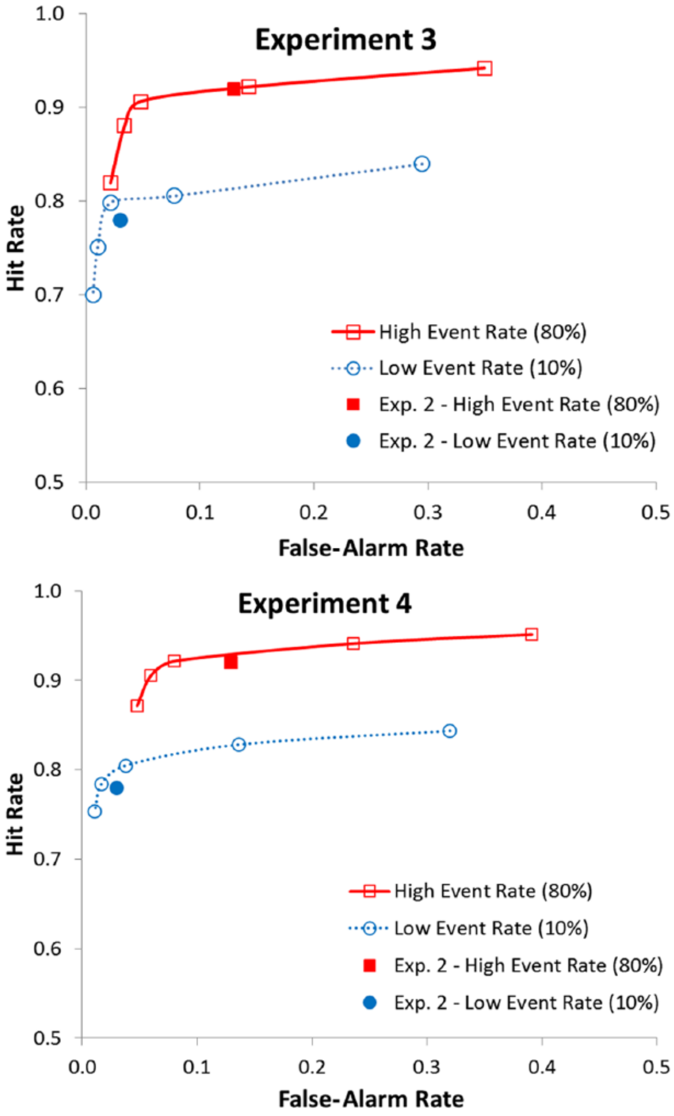

Figure 4. Receiver operating characteristic curves for low event rates (open circles) and high event rates (open squares) in Experiments 3 and 4. For comparison, also shown are the data from the binary yes/no judgment of Experiment 2 (filled symbols).

show that low event rate shifted bias toward reporting peripheral plane absence rather than presence.

The shape of the ROC curves appears to be a hybrid of competing theories. The curvilinear left-hand segments (corresponding to *target-present* responses) follow signal detection theory, which assumes a continuous distribution of evidence for signal presence. The linear right-hand segments (corresponding to *target-absent* responses), in contrast, follow threshold theory (Green & Swets, 1966; Swets, 1986), which assumes a nondetection state with no evidence of signal presence. Given no evidence of signal presence, the right-hand points differ only in the bias to guess that a target was present; the slope is just the ratio of target-present trials with guessing divided by target-absent trials with guessing.

If target-absent responses are genuine nondetections, then their location accuracy should be near chance probability (.25, given four possible target locations). Indeed, for target-present trials with a target-absent response, location accuracy was only .29. Furthermore, reports of target absence typically (about 2/3 of the time) came with the highest possible level of confidence in target absence, regardless of whether the plane was present (65%) or absent (69%).

In sum, the location accuracy and the ROC analysis provide converging evidence for a nondetection state, in which participants had no evidence of target presence and confidently reported *target absent*. There is no way to determine whether strength tags were never present for the trials resulting in the nondetection state (perhaps due to diversion of attention by the primary task) or whether some weak level of stimulus evidence was obtained but decayed before confidence level could be reported. In any case, the estimated probability of nondetection was clearly much higher at the low event rate (.20) than at the high event rate (.09).

EXPERIMENT 4

Experiment 3 showed that substantially decreasing peripheral event rate, from 80% of trials to 10% of trials (i.e., from 20% to 2.5% of individual conflict judgments), produced a significant drop in perceptual sensitivity for detecting peripheral planes. In Experiment 4, we investigated the extent to which this impairment could be nullified by making events more salient. In Experiments 1 through 3, we used a peripheral stimulus duration of 100 ms (for the purpose of investigating the vulnerability of different places in the central-task processing stream), even though that is much shorter than in most operational contexts. So, in Experiment 4, we investigated the more operationally relevant case in which the duration was 500 ms (i.e., 5 times as long). There was of course no guarantee that this change would make any difference; some have argued that peripheral attention is mainly attracted to stimulus onsets (a cue present even with 100-ms stimuli).

Method

The method was identical to that of Experiment 3, except for the fivefold increase in peripheral plane duration from 100 ms to 500 ms.

Participants. A new sample of 57 Oregon State University undergraduates participated in this experiment. Thirteen participants were excluded due to conflict judgment accuracy below our preset criterion of .8.

Results

Central conflict judgment. Mean RT for the conflict task was 929 ms and mean PC was .89. ANOVAs were conducted as a function of conflict judgment difficulty (easy vs. difficult). They revealed a significant effect of difficulty on RT (easy = 901 ms; difficult = 949 ms), $F(1, 43) = 14.17$, $p < .0001$, $\eta_p^2 = .25$, and PC (easy = .94; difficult = .83), $F(1, 43) = 100.62$, $p < .0001$, $\eta_p^2 = .70$.

Peripheral detection. The mean hit rate was .90, with only minor modulation by stimulus location (.92, .92, .89, and .88 for the left, top, right, and bottom locations, respectively). The Hit(CorLoc) rate was .87. The mean false-alarm rate was .04.

ANOVAs to assess the effects of SOA and conflict judgment difficulty on each dependent measure were based on data pooled across event rate due to sparse trials at low event rates. As in the previous experiments, hit rates were significantly higher at the 400-ms SOA (.92) than at the 600-ms SOA (.89), $F(1, 43) = 6.82$, $p < .05$, $\eta_p^2 = .14$ (see Figure 3). As in Experiment 3, conflict judgment difficulty did not influence hit rates (easy = .91; difficult = .90), $F < 1.0$ (see Figure 2). The interaction between conflict judgment difficulty and SOA was not significant for hit rate, $F < 1.0$. Conflict judgment difficulty did affect false-alarm rates, $F(1, 43) = 5.56$, $p < .05$, $\eta_p^2 = .11$ (easy = .03; difficult = .06). No other effects on false-alarm rates were significant. Hit(CorLoc) rate was similar at the 400-ms SOA (.88) and the 600-ms SOA (.87), $F(1, 43) = 1.54$, $p = .22$, $\eta_p^2 = .03$; central-task difficulty also had no main effect, $F(1, 43) = 2.80$, $p = .10$, $\eta_p^2 = .06$, and did not interact with SOA, $F < 1.0$.

A second set of ANOVAs was conducted on each dependent measure as a function of event rate. As shown in Table 1, lowering the event rate reduced hit rates (.92 to .80), $F(1, 43) = 15.92$, $p < .0001$, $\eta_p^2 = .27$; false-alarm rates (.08 to .04), $F(1, 43) = 13.39$, $p < .001$, $\eta_p^2 = .24$; and Hit(CorLoc) rates (.89 to .80), $F(1, 43) = 8.93$, $p < .01$, $\eta_p^2 = .17$.

Figure 4 (bottom panel) shows ROC curves for low event rate (open circles) and high event rate (open squares) in Experiment 4. The ROC curves closely resemble those of Experiment 3, again showing that lowering the event rate produced a modest loss of sensitivity. An ANOVA on AUCs showed a significant decrease in sensitivity for low event rate (AUC = .91) compared to high event rate (AUC = .94), $F(1, 42) = 4.31$, $p < .05$, $\eta_p^2 = .09$. There was no main effect of session order and no interaction between session order and event rate, *F*s < 1.0. Low event rate, in addition to lowering sensitivity, shifted bias toward fewer hits and fewer false alarms for each confidence rating (i.e., an increase in bias toward reporting plane absence).

Discussion

Experiment 4 replicated the main findings of our earlier experiments. The overall level of peripheral target detection and localization was very high and unaffected by central-task difficulty. In addition, the ROC curves again had curvilinear left-hand segments consistent with signal detection theory and linear right-hand segments consistent with threshold theory. Supporting the nondetection state hypothesized by threshold theory, the average accuracy of location judgments when participants reported plane absence was near chance (.27). The data again suggest that this nondetection state occurred more often on low-event-rate trials (.20) than on high-event-rate trials (.08).

The main purpose of Experiment 4 was to assess whether the reduction in hit rate at low event rates could be ameliorated by lengthening the duration of the peripheral event. Despite a fivefold increase in duration relative to Experiment 3 (from 100 to 500 ms), peripheral detection hit rate increased only modestly (.86 to .90), albeit significantly ($p < .05$). The modest improvement should be qualified by noting that due to the 500-ms exposure duration of the peripheral event in the left panel, it sometimes continued past the point at which participants responded to the conflict judgment in the right panel (especially at the 600-ms SOA). So, some or all of the quite modest improvement could reflect sequential processing of the peripheral target. The impact of event rate was similar between experiments; hence, increasing the peripheral event duration did not provide much protection against the costs of low event rate.

It might be intuitively surprising that such a large increase in duration did not have an even larger impact on overall peripheral detection success. One possible explanation is that only the onsets of peripheral stimuli have the power to strongly attract attention. If the onset is not noticed, the remainder of the duration of a static image might provide little further detection opportunity. A different result might be obtained with paradigms permitting, or even encouraging, deliberate scanning of the peripheral display. Also, a dynamically fluctuating icon (e.g., flashing) might improve detection by providing multiple onsets, each offering a quasi-independent opportunity for detection.

EXPERIMENT 5

The previous experiments showed high rates of peripheral detection during a difficult central conflict assessment task that demanded both spatial attentional resources and central cognitive resources. Nevertheless, participants did sometimes miss peripheral targets, even at high event rates. In the present experiment, we explored whether these misses are due to the absence of cognitive resources (already engaged by the central task) to assist with peripheral detection. What would happen if we reduced the cognitive-processing resources required by the central task, allowing those resources to be allocated to peripheral detection? Would detection of peripheral events improve, perhaps even approaching error-free performance?

We wanted to match the visual viewing conditions used so far, so we designed a right-panel task that would require participants to fixate and attend central stimuli (as in Experiments 1 through 4) but, in key conditions, require minimal cognitive processing. The right-panel task chosen was detecting a small gap in a circle. The gap was tiny enough to require foveating the circle. On half of the trials, chosen at random, no circle appeared. With no right-panel stimulus to respond to, the processing resources required should be especially low. This condition is the closest we can come to a “peripheral-task-only” control condition while still requiring fixation of the right panel (so that the retinal locations of peripheral planes match preceding experiments).

We presented the peripheral left-panel target for 100 ms (as in Experiments 1 through 3) at the same time the central target appeared (i.e., the SOA was 0 ms). This combination of conditions ensured that participants could not gain by triggering an eye movement to the periphery when they realized that there was no central stimulus. By the time a shift could take place, the peripheral stimulus would have already disappeared.

Note that all of the conditions in this gap-detection experiment require less central cognitive processing than the previous experiments, which involved assessing a complex geometrical relationship (future plane conflict). Common sense suggests that the ordering of the degree of central cognitive processing required by the present three conditions from least to most would be (a) no circle stimulus, (b) circle without a gap, and (c) circle with a gap to detect. One could instead propose that the no-stimulus condition would be difficult due to prolonged search for the circle, but it seems unlikely given that the circle appeared at a predictable place and time.

Method

The method was identical to that of Experiment 1, except for alteration of the central (right-panel) task. Instead of plane icons, the stimulus in each quadrant was an unfilled white circle in the quadrant center (diameter = 2.29° of visual angle). The circle appeared on only half of the trials, randomly selected. When a circle was present, participants pressed the *1* key on the numeric keypad if the circle had a gap or pressed the *3* key if it did not. When no circle was displayed, participants could simply wait for the next trial; this no-circle condition, unlike the others, requires no selection or execution of a response. The gap was narrow in extent (0.23°), in a variable location on the circle (top, bottom, left, or right). Pilot testing showed that the task was difficult (not all participants could reach 90% correct) but could be performed reasonably accurately if, and only if, the circle was foveated. The sequence of events for each quadrant within a trial began with a fixation cross, on for 500 ms and then off for 500 ms, ensuring that participants knew the location of the upcoming stimulus.

As in all of our earlier experiments, the location of the circle moved clockwise around the four quadrants of the right panel on each trial. The SOA between the circle and the peripheral event was always 0 ms. The peripheral left-panel display and task were identical to our previous experiments, with a peripheral event on 80% of trials (as in Experiment 1).

Participants. A new sample of 29 Oregon State University undergraduates completed this experiment. Nine participants were excluded because their primary gap judgment accuracy fell below our preset criterion of .8.

Results

Central gap judgment. Gap judgment responses were made with a mean RT of 623 ms and mean PC of .91. ANOVAs were conducted on these data as a function of circle type (circle with gap vs. circle without gap) and peripheral stimulus (plane present vs. plane absent).

For RT, there was no significant difference between circle-with-gap RT (618 ms) and circle-without-gap RT (629 ms), $F < 1.0$. However, presence/absence of the left-panel peripheral plane had a modest (31 ms) but significant effect on gap judgment RT (plane present = 639 ms; plane absent = 608 ms), $F(1, 19) = 5.46$, $p < .05$, $\eta_p^2 = .22$. RT showed no significant interaction between the two variables, $F(1, 19) = 2.87$, $p = .11$, $\eta_p^2 = .13$.

The difference in PC between circle-with-gap trials (.93) and circle-without-gap trials was not significant (.89), $F(1, 19) = 3.93$, $p = .0621$, $\eta_p^2 = .17$. PC was higher on plane-present trials (.92) than on plane-absent trials (.90), $F(1, 19) = 7.60$, $p < .05$, $\eta_p^2 = .29$. The interaction between these two variables was not significant, $F(1, 19) = 1.09$, $p = .3093$, $\eta_p^2 = .05$.

Peripheral detection. The mean peripheral hit rate was .94, with little variation across stimulus locations (.95, .94, .94, and .94 for the left, top, right, and bottom locations, respectively). The mean peripheral Hit(CorLoc) rate was .88. The mean peripheral false-alarm rate was .16.

We performed ANOVAs for each peripheral detection measure as a function of circle type (no circle, circle without gap, and circle with gap). As shown in Table 3, peripheral hit rates were high and stable across circle types (no circle = .93,

TABLE 3: Task Performance as a Function of Central Stimulus Type (Circle With Gap, Circle Without Gap, and No Circle) in Experiment 5

	Central Gap Judgment		Peripheral Detection		
Central Stimulus	RT	PC	Hit	FA	Hit(CorLoc)
Circle with gap	618 (34)	.93 (.02)	.95 (.03)	.12 (.05)	.90 (.03)
Circle without gap	629 (39)	.89 (.02)	.95 (.04)	.17 (.06)	.88 (.04)
No circle	—	—	.93 (.05)	.18 (.05)	.87 (.05)

Note. RT = response time; PC = proportion correct; FA = false-alarm rate; Hit(CorLoc) = probability of detecting the peripheral target and correctly reporting its location. The standard error of the mean is shown in parentheses.

circle without gap = .95, circle with gap = .95, $F < 1.0$). Peripheral-task false-alarm rates were lower for the circle-with-gap condition (.12) than for the no-circle (.18) and circle-without-gap (.17) conditions, $F(2, 38) = 3.98$, $p < .05$, $\eta_p^2 = .17$. Peripheral-task Hit(CorLoc) rate was also consistent across circle types (no circle = .87, circle without gap = .88, circle with gap = .90, $F < 1.0$).

Discussion

For the central task in Experiment 5, we used a gap/no-gap discrimination designed to be sufficiently difficult to require participants to closely fixate each stimulus location. On a randomly selected half of the quadrants, the circle did not appear (no-circle condition) and no-gap judgment or response was made. We expected that this condition would require the least cognitive effort and therefore produce the highest peripheral detection performance. However, that result was not observed. Mean peripheral-task hit rate in the no-circle condition was .93, actually slightly lower (but not significantly so) than when a circle did appear and a gap judgment response was made (.95). The upper bound of the 95% confidence interval is only a .01 effect in the predicted direction, so the data rule out all but a negligible cost of what appears to be greater cognitive effort on the central right-panel task. The no-circle hit rate is also very close to (and not higher than) that of Experiment 1 (.94), in which the central task required a complex perceptual analysis and response in every quadrant. Thus, performance on the peripheral task was not improved for no-circle trials, despite the greatly reduced level of cognitive processing needed.

Apparently, any cognitive resources freed up in the no-circle condition were not beneficial for peripheral detection. This result is consistent with our failure to find difficulty effects in each of the four previous experiments, but it adds to the difficulty in explaining our SOA results. One would have thought that the no-circle condition would remove whatever cognitive activities were present at longer SOAs that were draining mental resources away from peripheral detection, but the results provide no support for this view.

Taken at face value, the consistent lack of central-task difficulty effects on peripheral detection supports an "interrupt processing" hypothesis: Arrival of a peripheral stimulus elicits whatever processing resources are needed to take note of that stimulus. According to this hypothesis, peripheral detection proceeds automatically regardless of how much cognitive processing is required by the central task, ranging from complex assessments of aircraft trajectories to simple judgments that no circle stimulus is present. This tentative conclusion is both powerful and surprising, and with surprise should come a healthy dose of skepticism. We demand more evidence for surprising conclusions. It is important for authors of future research to explore difficulty manipulations across a wider range of cognitive judgments for the central task and including higher levels of difficulty than any used in the present experiments.

GENERAL DISCUSSION

Over the past several decades, the problem of maintaining situation awareness has been recognized as critical in many domains requiring complex human-automation interactions, including aircraft cockpits (Woods & Sarter, 2010). In the present research, we tested the feasibility of picking up useful new information from a peripheral display while working on a cognitively demanding task with foveated stimuli. Overall, the present results are surprisingly positive, given several major obstacles to peripheral detection: (a) a heterogeneous background in the peripheral display rather than a plain dark background; (b) considerable uncertainty about the spatial location and arrival time of the peripheral target; (c) large target eccentricities, up to 30° of visual angle; (d) a central task requiring a nearly continuous sequence of demanding relational judgments on object pairs, with little opportunity to deliberately scan the peripheral display; (e) targets too brief (100 ms) for even a reflexive gaze shift; and (f) delayed reporting of peripheral targets (typically by several seconds, until the sequence of four conflict judgments was finished).

Despite these challenging conditions, participants with only modest training were able to detect and locate targets at a high overall level of accuracy and store this information for a delayed report. Across Experiments 1 through 5, mean hit rate was .91 and mean Hit(CorLoc), detection with correct location, was .87. The fact that these two numbers are so similar indicates that (a) most hits were genuine target detections and (b) target detection reliably leads to localization. The latter conclusion is consistent with the basic research suggesting that location tagging of percepts is typically automatic, riding “piggyback” on the detection itself (Johnston & Pashler, 1990).

Just as most hits were genuine target detections, most misses were genuine detection failures, a conclusion based on three converging lines of evidence. First, the right-hand segments of the ROC curves were collinear with (1.0, 1.0), which is the classic signature of threshold theory. Second, location accuracy for the misses, averaged across Experiments 3 and 4, was only .28, which is only a smidgeon above the chance guessing levels with four possible locations (.25). Third, on about two thirds of the miss trials, participants expressed the highest possible level of confidence in target absence. Taken together, these findings support the hypothesis of a nondetection state on almost all trials with a *target-absent* response. An implication of this finding is that for conditions yielding misses (e.g., low event rate), the problem cannot be solved merely by encouraging operators to adopt a more lenient criterion for detection. Instead, the opportunity for detection must somehow be improved by, for example, increasing stimulus energy or salience.

Effects of Degree of Eccentricity

Our experimental conditions sampled a wide range of eccentricities—from 12° to 30°—separating the locations of the foveated central-task stimulus and the peripheral target. Over this range, analyses showed no significant effect of eccentricity on peripheral hit rates. Note, however, that these experiments were not designed to examine eccentricity effects. Target locations in the left panel were not equated for background heterogeneity or for relative contrast.

To better assess eccentricity effects free of confounding factors, we carried out a control experiment with the same central task as the other experiments but with a homogenous blue background for the detection task (similar to the sky color from Experiments 1 through 5). We used four peripheral target locations equally spaced along the horizontal midline, ranging from 15.8° to 26.8° of visual angle from the center of the right panel. The event rate was the same as in Experiment 1: 80% of trials (20% of conflict judgments). Results showed very high detection performance with no effect of eccentricity; the hit rate was .95 at each of the peripheral four locations. These results are consistent with the vision literature for relatively large high-contrast stimuli displayed against a homogenous dark background (e.g., Rinalducci et al., 1989; Rinalducci & Rose, 1986) and extend those results to conditions with somewhat lower-contrast stimuli displayed against a relatively bright, heterogeneous field. Peripheral vision appears to have evolved largely for detecting stimulus changes, so using it for that purpose is a good fit to human capabilities. It seems likely that detection decrements would emerge with still greater eccentricities, with lower contrast stimuli, or with a peripheral task that requires stimulus discrimination rather than detection.

Effects of SOA

To assess the vulnerability to missed detection of peripheral targets across different stages of central-task processing, we manipulated the SOA between the tasks (400 vs. 600 ms). A priori, it was plausible that either SOA might have had the worst impact on performance. The alternatives can be understood in terms of Johnston, McCann, and Remington's (1995) distinction between "spatial attention," which governs early visual processing, and "central attention," which governs later cognitive processing (including the central bottleneck underlying the psychological refractory period effect). At the 400-ms SOA, the main risk is that the peripheral target will occur while spatial attention is concentrated far away from the peripheral stimulus. At the 600-ms SOA, the main risk is that the peripheral target will occur while central attention is working on central stages of cognitive processing, including making stimulus decisions, selecting responses, and supervising their execution.

In all five experiments, we found that peripheral detection was worse at the longer SOA. This consistent finding suggests that the greater risk of missing a peripheral target comes not from spatially attending to a distant location but from the engagement of cognitive-processing resources by a different cognitive task. This finding is consistent with studies showing that later/deeper cognitive processes (e.g., response selection) can disrupt shifts of spatial attention (Brisson & Jolicoeur, 2007; Lien et al., 2011) and impair peripheral stimulus processing (Chan & Courtney, 1993).

Minimal Effects of Central-Task Difficulty

The present experiment included substantial variation in the difficulty of the central conflict judgment—easier when nonconflict planes were on diverging paths rather than converging paths—confirmed by strong effects on both accuracy and RT in each experiment. Surprisingly, these empirically validated increases in the difficulty of central conflict judgments did not impair peripheral detection in any of the five experiments. Averaged across Experiments 1 through 4, mean hit rate was .90 in the easy condition and .91 in the difficult condition; similarly, mean Hit(CorLoc) was .87 in the easy condition and .87 in the difficult condition. If we pool the large samples from all four experiments, the 95% confidence interval for the difficulty effect excludes any true effect larger than a negligible reduction of .004. The lack of a difficulty effect cannot be easily dismissed due to ceiling effects, because other independent variables (SOA and event rate) produced statistically significant effects on the same dependent variables.

It is striking that harder cognitive work on the central task did not further undermine peripheral detection. This finding was confirmed in Experiment 5 with an even more extreme manipulation of central-task difficulty. Participants made a simple judgment of whether a circle did or did not contain a gap, but this judgment was required only on half of the trials where a circle was actually displayed. The no-circle trials provide a case of extremely low cognitive workload, since there was no need for gap detection, response selection, or response execution. Nevertheless, the peripheral detection hit rate was no lower when the circle appeared (.95 when it had a gap, .95 when it had no gap) than when it did not appear at all (.93). Similarly, Nikolic et al. (2004) previously reported no impact of *Tetris* difficulty on detection of a peripheral box (with peripheral stimulus durations much longer than ours). Although it is premature to conclude that task difficulty never matters for peripheral detection—and we strongly encourage future investigations, perhaps going further up the scale of increasing difficulty—it may be approximately true for a wide range of practical applied conditions.

Minimal Degradation of Central Task Performance

Woods and Sarter (2010) recently emphasized the importance to situation awareness of being able to attend to multiple information sources with minimal interference on the main task. In many applied situations (especially in aviation), any substantial interference with the foveated task (often critical for immediate safety) would not be acceptable.

TABLE 4: Mean Response Time (in ms) to the Central Conflict Judgment for Each Quadrant as a Function of When the Peripheral Plane Appeared

	Quadrant for Central Conflict Judgment			
Conflict Quadrant Active When Peripheral Plane Appeared	1	2	3	4
1	930	990	900	861
2	866	929	977	889
3	866	872	1013	967
4	864	881	943	1010
Absent	852	862	920	901

Note. Shaded cells represent trials in which the peripheral plane appeared while participants were responding to the central conflict pair.

The present study was primarily designed to study the impact of engagement in demanding central judgment on peripheral detection, not the other way around. Nevertheless, the data can shed some light on this issue. Specifically, it is possible to determine what happens to central conflict judgments before, during, and after a peripheral target has been found. Detection of the peripheral event might interfere with the concurrent conflict judgment, and possibly the following one as well, due to encoding into short-term memory. However, any subsequent conflict responses might benefit from removal of the need to monitor the other panel.

Table 4 shows mean conflict RT in Experiment 1 (which has the most data due to the 80% event rate) from trials in which participants correctly reported the location of a plane (or its absence). What this table clearly shows is that there is a modest cost of peripheral detection (roughly 60 to 80 ms) on the concurrent conflict judgment (see the shaded diagonal). This cost is not unexpected given the well-known cost of finding targets rather than merely looking for them (cf. Duncan, 1980). There also appears to be a cost on the trial immediately following detection (the cells above the shaded diagonal), although smaller in size, which might reflect storing events with location tags into short-term memory while the next conflict pair appears. Note that our paradigm requires “access awareness,” producing a lasting, queriable representation, rather than just evanescent “phenomenal awareness” (Lamme, 2003). It is less clear from our data whether removing the need to monitor the periphery (after finding a target in an earlier quadrant) benefited central task performance. The cells above the shaded ones (central task following detection) have similar mean RT to those below the diagonal (preceding detection).

Effects of Event Rate

In Experiment 1, the peripheral event rate per trial was 80%. Although not reported here, an earlier experiment that compared 80% event rates to 40% event rates found a negligible effect. However, when we further reduced the event rate to only 10% in Experiments 2 through 4, the average hit rate dropped substantially from about .92 to .79 (see Table 1).

The lower hit rate was accompanied by a substantial decrease in the false-alarm rate, suggesting a criterion shift caused by the fact that *present* was less often the correct answer. With the binary present/absent detection task used in Experiment 2, it was difficult to assess whether there was also any loss in sensitivity to peripheral targets. Experiments 3 and 4, however, used a 6-point confidence rating scale that allowed extraction of full ROC curves. Both experiments showed that relative to the 80% event rate, a 10% event rate produced a statistically significant decline in sensitivity for detecting peripheral stimuli. We conclude that peripheral detection can be highly successful for high and medium event rates but becomes less successful at much lower event rates. Clearly, this finding represents a concern for display design and may set a boundary condition for successful applications.

Further Research

Overall, our results showed reliable peripheral event detection, even 30° in the periphery, remarkably resistant to degradation by our central-task difficulty manipulations. This is an important result that offers considerable promise for field applications, but much more needs to be done to characterize the "window of opportunity." Research is needed to further assess how detection performance is affected by the depth and duration of central processing; it is important to examine a wide variety of perceptual and cognitive judgments. Work is also needed to determine how well operators can discriminate perceptual properties of peripheral stimuli, such as color; we found accurate reporting of location, but this fundamental feature might be a special case. It is also important to examine training effects, which might be positive (by reducing mental resource demands) or negative (due to complacency and/or a deeper cognitive commitment to the central task).

ACKNOWLEDGMENTS

This research was supported by the NASA Aviation Safety program; we thank especially Michael Feary, Kara Latorella, Randy Bailey, and Jessica Nowinsky for their assistance. We also thank Eric Adamic and Eamon Dick for their help running the experiments.

KEY POINTS

- People can reliably detect brief, high-contrast events in a peripheral display, even while already engaged with a cognitively demanding task in a central vision.
- Peripheral detection performance is high across substantial variations in visual eccentricity (12°–30°) and central-task difficulty.
- Peripheral detection success may decline significantly with drastic reductions in event rate.
- The risk of missing a peripheral event was lower if it occurred during early perceptual processing on the central task and higher during later cognitive processing.

REFERENCES

Brisson, B., & Jolicoeur, P. (2007). Electrophysiological evidence of central interference in the control of visuospatial attention. *Psychonomic Bulletin & Review*, *14*, 126–132.

Chan, H. S., & Courtney, A. J. (1993). Effects of cognitive foveal load on a peripheral single-target detection task. *Perceptual and Motor Skills*, *77*, 515–553.

Duncan, J. (1980). The locus of interference in the perception of simultaneous stimuli. *Psychological Review*, *87*, 272–300.

Endsley, M. R. (2000). Theoretical underpinnings of situation awareness: A critical review. In M. R. Endsley & D. J. Garland (Eds.), *Situation awareness analysis and measurement* (pp. 3–32). Mahwah, NJ: Lawrence Erlbaum.

Folk, C. L., Remington, R. W., & Johnston, J. C. (1992). Involuntary covert orienting is contingent on attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance*, *18*, 1030–1044.

Granada, S., Dao, A. Q., Wong, D., Johnson, W. W., & Battiste, V. (2005, April). *Development and integration of a human-centered volumetric cockpit display for distributed air-ground operations*. Paper presented at the 12th International Symposium on Aviation Psychology, Oklahoma City, OK.

Green, D. M., & Swets, J. A. (1966). *Signal detection theory and psychophysics*. New York, NY: Wiley.

Hameed, S., Ferris, T., Jayaraman, S., & Sarter, N. B. (2009). Using informative peripheral visual and tactile cues to support task and interruption management. *Human Factors*, *51*, 126–135.

Hurvich, L. M., & Jamison, D. (1966). *The perception of brightness and darkness*. Boston, MA: Allyn & Bacon.

Johnston, J. C., McCann, R. S., & Remington, R. W. (1995). Chronometric evidence for two types of attention. *Psychological Science*, *6*, 365–369.

Johnston, J. C., & Pashler, H. E. (1990). Close binding of identity and location in visual feature perception. *Journal of Experimental Psychology: Human Perception and Performance*, *16*, 843–856.

Lamme, V. A. F. (2003). Why visual attention and awareness are different. *Trends in Cognitive Sciences*, *7*, 12–18.

Lien, M.-C., Croswaite, K., & Ruthruff, E. (2011). Controlling spatial attention without central attentional resources: Evidence from event-related potentials. *Visual Cognition*, *19*, 37–78.

Lien, M.-C., Ruthruff, E., Goodin, Z., & Remington, R. W. (2008). Contingent attentional capture by top-down control settings: Converging evidence from event-related potentials. *Journal of Experimental Psychology: Human Perception and Performance*, *34*, 509–530.

Lien, M.-C., Ruthruff, E., & Johnston, J. C. (2006). Attentional limitations in doing two things at once: The search for exceptions. *Current Directions in Psychological Science*, *15*, 89–93.

Lien, M.-C., Ruthruff, E., & Johnston, J. C. (2010). Attention capture with rapidly changing attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance*, *36*, 1–16.

Nikolic, M. I., Orr, J. M., & Sarter, N. B. (2004). Why pilots miss the green box: How display context undermines attention capture. *International Journal of Aviation Psychology*, *14*, 39–52.

Pashler, H., & Johnston, J. C. (1989). Chronometric evidence for central postponement in temporally overlapping tasks. *Quarterly Journal of Experimental Psychology, 41A*, 19–45.

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology, 32A*, 3–25.

Prinzel, L. J., Kramer, L. J., Arthur, J. J., Bailey, R. E., & Comstock, J. R. (2005). *Flight test evaluation of situation awareness benefits of integrated synthetic vision system technology for commercial aircraft*. Hampton, VA: NASA Langley Research Center.

Rinalducci, E. J., Lassiter, D. L., MacArthur, M., Piersal, J., & Mitchell, L. K. (1989). Further experiments on the effects of foveal load on peripheral vision. In *Proceedings of the Human Factors Society 33rd Annual Meeting* (pp. 1450–1453). Santa Monica, CA: Human Factors and Ergonomics Society.

Rinalducci, E. J., & Rose, P. N. (1986). The effects of foveal load on peripheral visual acuity. *Proceedings of the Human Factors Society 30th Annual Meeting* (pp. 608–610). Santa Monica, CA: Human Factors and Ergonomics Society.

Smith, T., & Guild, J. (1931). The C.I.E. colorimetric standards and their use. *Transactions of the Optical Society*, *33*, 73–134.

Swets, J. A. (1986). Indices of discrimination or diagnostic accuracy: Their ROCs and implied models. *Psychological Bulletin*, *99*, 100–117.

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*, *26*, 799–806.

Winer, B. J. (1962). *Statistical principles in experimental design*. New York, NY: McGraw-Hill.

Wolfe, J. M., Horowitz, T. S., & Kenner, N. M. (2005). Rare items often missed in visual searches. *Nature*, *26*, 439–440.

Woods, D. D., & Sarter, N. B. (2010). Capturing the dynamics of attention control from individual to distributed systems: The shape of models to come. *Theoretical Issues in Ergonomics Science*, *11*, 7–28.

Wyszecki, G. (1986). Color appearance. In K. R., Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. 1. Sensory processes and perception* (pp. 9-1–9-57). New York, NY: Wiley.

Yantis, S. (1993). Stimulus-driven attentional capture and attentional control settings. *Journal of Experimental Psychology: Human Perception and Performance*, *19*, 676–681.

Yantis, S., & Jonides, J. (1984). Abrupt visual onsets and selective attention: Evidence from visual search. *Journal of Experimental Psychology: Human Perception and Performance*, *10*, 601–621.

James C. Johnston is a research psychologist in the Human Systems Integration Division at the NASA Ames Research Center. He received his PhD in psychology from the University of Pennsylvania in 1974.

Eric Ruthruff is an associate professor in the Psychology Department at the University of New Mexico. He received his PhD in psychology from the University of California–San Diego in 1995.

Mei-Ching Lien is an associate professor in the School of Psychological Science at Oregon State University. She received her PhD in psychology from Purdue University in 2001.

Date received: October 1, 2012
Date accepted: June 20, 2014