Attentional oblique effect when judging simultaneity

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We extended the investigation of the oblique effect in two novel ways: from stimulus-driven vision to visual attention and from space to time. Participants fixated the center of briefly flashed displays that contained a temporally varying Gabor stimulus in each of the four peripheral quadrants. Across trial blocks, we manipulated which two of the four peripheral stimuli were to be selected for a simultaneity judgment. Simultaneity judgments were significantly worse for obliquely (diagonally) attended targets than for cardinally (horizontally or vertically) attended targets, despite identical retinal stimulation across all attentional conditions. The impairment in judging the simultaneity of obliquely attended targets occurred between and within lateral hemifields, despite significantly greater temporal acuity for the left hemifield. The oblique effect in simultaneity judgments disappeared when the same targets were presented without temporally varying stimuli at distractor locations—a finding that implicates selective attention. Intriguingly, the oblique effect in excluding stimuli at distractor locations also disappeared when participants viewed the original displays but attended to spatial frequency rather than to simultaneity. These findings raise the possibility of different spatial integration windows when attending to spatial versus temporal features, even when those features are co-presented in space and time.

Keywords: attention, oblique effect, temporal precision, spatial integration, visual field anisotropy, left visual field advantage


Introduction

This study explored novel extensions of a well-known visual phenomenon, the oblique effect. Reported first by Mach (1861), the oblique effect is an anisotropy characterized by lower sensitivity to diagonally (obliquely) oriented stimuli than to horizontally or vertically (cardinally) oriented stimuli. Not just a human phenomenon, the oblique effect occurs in non-human species as evolutionarily distant from each other as the octopus and the monkey (Appelle, 1972). Single-cell recordings from the cat primary visual cortex suggest that the oblique effect arises from an overrepresentation of visual neurons tuned to cardinal axes (Li, Peterson, & Freeman, 2003; Mansfield, 1974). This physiological anisotropy implies a steady-state explanation of the oblique effect, as the overrepresentation of cardinally tuned neurons can be construed as a static characteristic of the visual cortex.

Other evidence indicates that the oblique effect is neither static nor explainable solely by the overrepresentation of cardinally tuned cortical cells. For example, psychophysical experiments using precisely timed noise masks to limit neural persistence have demonstrated that the oblique effect in orientation discrimination is dynamic, emerging gradually across the tens of milliseconds following stimulus presentation (Matthews, Rojewski, & Cox, 2005). The same study also revealed that, to achieve a given level of orientation discrimination, significantly longer stimulus durations are needed for oblique than for cardinal stimuli. It is tempting to explain the comparatively sluggish neural response to oblique stimuli by probability summation, given the overrepresentation of cardinally tuned neurons. However, the overrepresentation of cardinally tuned neurons is insufficient to explain two other observations. First, the oblique effect is more pronounced when the discriminanda are presented successively rather than simultaneously (Heeley & Buchanan-Smith, 1992; Matthews et al., 2005; Westheimer, 2003). Second, Westheimer (2003) demonstrated a significant oblique effect even for judging the orientation of an imaginary line between two circles—stimulation that would not generate strong orientation-specific responses in the primary visual cortex. From these observations, Westheimer conjectured “that the neural locus for the oblique effect is more central than the primary visual cortex” (p. 2281).

Westheimer’s (2003) conjecture raises the question of how far the oblique effect extends beyond what would be predicted by the spatial tuning properties of cortical neurons. Here, we extend the investigation of the oblique effect in two ways: from stimulus-driven vision to visual attention and from space to time. Participants fixated the center of briefly flashed displays that contained a temporally varying Gabor stimulus in each of the four peripheral quadrants. Across trial blocks, we manipulated which two of the four peripheral stimuli were to be selected for a simultaneity judgment. The attended targets were aligned either cardinally or obliquely. However, unlike the above-mentioned studies (Heeley & Buchanan-Smith, 1992; Matthews et al., 2005; Westheimer, 2003), the present study...
did not require participants to judge either local or global orientation. Consequently, the overrepresentation of cardinality tuned cortical cells (Li et al., 2003; Mansfield, 1974) and the previously reported sluggish temporal response to obliquely oriented stimuli (Matthews et al., 2005) were irrelevant to the present attention-based simultaneity judgments.

Our approach to investigating an attentional oblique effect in simultaneity judgments was based on signal detection theory (Green & Swets, 1966). This facilitated the interpretation of two error types that can happen when judging whether two events occur simultaneously versus asynchronously. A “miss” occurs when a participant fails to report a temporal asynchrony that is present in the targets. A “false alarm” occurs when a participant reports a temporal asynchrony that is not present in the targets. The pattern of misses and false alarms can be informative when teasing apart various factors that might generate an attentional oblique effect. For example, one would expect both more misses and more false alarms for obliquely versus cardinally attended targets if the attentional oblique effect simply reflects increased neural noise. By contrast, one would expect more oblique than cardinal misses, but no difference in false alarms, if the attentional oblique effect reflects lower temporal acuity. Conversely, one would expect more oblique than cardinal false alarms, but no difference in misses, if the attentional oblique effect reflects a failure to exclude temporally varying distractors, i.e., stimuli from task-irrelevant locations. Of course, *d′* from signal detection theory (SDT) controls for mere trade-offs between misses and false alarms (response-bias shifts) that might co-vary with obliquely versus cardinaly attended targets.

To summarize briefly, we report two main findings. First, misses and false alarms (response-bias shifts) might generate an attentional oblique effect. For example, one would expect both more misses and more false alarms for obliquely versus cardinaly attended targets if the attentional oblique effect simply reflects increased neural noise. By contrast, one would expect more oblique than cardinal misses, but no difference in false alarms, if the attentional oblique effect reflects lower temporal acuity. Conversely, one would expect more oblique than cardinal false alarms, but no difference in misses, if the attentional oblique effect reflects a failure to exclude temporally varying distractors, i.e., stimuli from task-irrelevant locations. Of course, *d′* from signal detection theory (SDT) controls for mere trade-offs between misses and false alarms (response-bias shifts) that might co-vary with obliquely versus cardinaly attended targets.

**Experiment 1a: Simultaneity judgments across hemifields**

**Methods**

**Apparatus**

All experiments reported here were conducted on a 24-in. (60.96 cm) flat screen Apple LED Cinema Display that was controlled by a Macintosh Pro 4 Tower computer. The computer ran on a Mac OS X version 10.5.6 operating system. Matlab software called functions from the psychophysics toolbox (Brainard, 1997; Pelli, 1997). The vertical refresh rate of the monitor was 60 Hz, and the spatial resolution was 1024 × 768 pixels. A chin rest helped stabilize head position at 57 cm from the monitor.

**Targets and distractors**

The targets and distractors were achromatic Gabor patches, created by multiplying a sinusoidal luminance profile by a two-dimensional Gaussian envelope. The Gabor patches had maximum (108.00 cd/m²) and minimum (5.83 cd/m²) luminances that rendered high contrast (Michelson contrast = 89.76%) within the apparently gray surround (16.1 cd/m²). The spatial frequency was 1.25 cycles per degree; each Gabor patch comprised four randomly phase-shifted light–dark cycles that collectively spanned a 3.2 × 3.2 degree (84 × 84 pixel) square region. The orientation of each Gabor patch was chosen randomly from the full 360-degree range.

**Stimulus sequence**

**Standard 4-Gabor condition**

The stimulus sequence for a sample trial in our standard 4-Gabor condition is schematized in Figure 1A. Each trial began with a central fixation marker shown simultaneously with a pair of peripheral cues (Figure 1A). The fixation marker was a small gray square (16.1 cd/m²; 0.44 deg or 12 pixels per side) that was inscribed in a larger square (1.33 deg or 36 pixels per side) of noise that rendered the central letter difficult to identify unless fixated directly. The peripheral cues were equiluminant solid red circles (16.1 cd/m²; CIE 0.615, 0.345; 3.2-deg (84 pixel) diameter) positioned where the two Gabor targets were to appear. A computerized voice immediately preceding the peripheral visual cues also indicated whether the two Gabor targets would be in the “top,” “bottom,” “left,” “right,” “diagonal up,” or “diagonal down” corners.

After 350 ms, the peripheral cues were replaced by the gray surround (16.1 cd/m²) for 200 ms (Figure 1B). Gabor targets then appeared at the cued positions for 200 ms, concurrently with two other Gabor patches (“distractors”) in the non-cued corners (Figure 1C). Each corner’s Gabor patch was centered 16.2 deg diagonally from fixation and 22.91 deg from the Gabor patch in each adjacent corner—well beyond the critical region for spatial crowding1 (Toet & Levi, 1992). For the next 66 ms, each corner’s Gabor patch either remained the same or changed orientation by 90 degrees, independent of the other Gabor patches. In the sample trial schematized in Figure 1, only the upper right Gabor patch (indicated by the green arrow) has changed orientation at this point in the sequence (Figure 1D). For the next 100 ms, one of ten randomly selected lowercase letters (31.20 cd/m²; 31.92% contrast; 12-point Helvetica font)
appeared at fixation (Figure 1E; an “n” in our schematic). For the next 34 ms, the central letter was replaced by a noise mask having parameters identical to those in its surround (Figure 1F). During the final 200 ms, the corner Gabor patches that had not previously changed orientation by 90 degrees now did so, as schematized by the green arrows in Figure 1G.

Two-Gabor condition

A variation on the standard 4-Gabor condition is schematized in Figure 2. Our 2-Gabor condition was identical to the standard 4-Gabor condition in all ways except for the absence of the “distractor” Gabor patches in the two non-cued corners. The 2-Gabor condition probed how performance would change, relative to the standard 4-Gabor condition, when Gabor targets did not have to be selected to the exclusion of Gabor distractors—an attentional requirement.

Task

The task on each trial was two-fold. First, to ensure control of fixation, the participant was required to correctly identify the central letter (Figure 1H). An incorrect letter response immediately aborted the trial and automatically restarted the trial sequence. Second, after making a correct letter response, the participant judged peripheral simultaneity, i.e., indicated whether the two cued peripheral Gabor targets changed orientation at the same time or at different times (Figure 1I). To maintain motivation, immediate auditory feedback identified each letter response and each simultaneity response as either correct or incorrect. The computer also announced the percentage of correct letter responses and the percentage of correct simultaneity responses after every 90 trials.

Participants

Denison University’s Human Subject Committee approved all experiments in this study, which were conducted with the understanding and written consent of each participant. All participants in the study had normal or corrected-to-normal acuity. Eighteen naive Denison University undergraduates completed Experiment 1a.

Procedure

Each participant first completed a series of practice blocks to establish that the task could be performed at greater-than-chance levels before the actual trials began. Each participant then completed 240 actual trials, according to a two (stimulus type) by six (target-quadrant pair) design. The two stimulus types were the standard 4-Gabor stimulus and the 2-Gabor stimulus. The six target-quadrant pairs were “top,” “bottom,” “left,” “right,” “diagonal up,” and “diagonal down.” For data analysis (see below), these six target-quadrant pairs were grouped into three attentional conditions (horizontal, vertical, diagonal). During the experiment, trials were blocked by target-quadrant pair, with twenty trials in each of twelve blocks, two blocks for each of the six target-quadrant pairs. The standard 4-Gabor condition and 2-Gabor condition were randomly interleaved.
within each block. The order of target-quadrant pairs was counterbalanced for each participant.

To avoid floor and ceiling effects, the computer assessed each participant’s performance every 90 trials (a complete set of the three attentional conditions), altering the stimulus duration when necessary. The stimulus durations were 600 (the default duration, Figures 1C to 1G), 300, or 900 ms. At each reevaluation point, if the participant’s simultaneity judgments ranged between 60% and 80% correct the current stimulus duration was retained. Performance below 60% or above 80% correct, respectively, triggered 300-ms increases or decreases (50% of the durations shown in Figures 1C to 1G), until reaching our maximum (900 ms) or minimum (300 ms) durations. This procedure generated peripheral onset-to-onset asynchronies (Figures 1D to 1G) of 100, 200, or 300 ms, depending on the participant’s performance. Critically, this performance-driven adjustment to the stimulus duration produced fixation-letter durations (Figure 1E) of just 50, 100, or 150 ms, which are too brief to permit reliable eye movements.

Procedure: Data analysis

All statistics reported in this study were based on a completely within-subject experimental design. In Experiment 1a, the independent variables were attentional condition (horizontal, vertical, diagonal) and stimulus condition (the standard 4-Gabor condition and the 2-Gabor condition). The dependent variable was $d'$, computed according to standard signal detection procedures (Green & Swets, 1966). Hits and false alarms were defined as correct and incorrect “different” responses, respectively. The miss rate was defined as 1.0 minus the hit rate.

Rather than adjusting alpha levels by arbitrary amounts a priori or post hoc, we assessed the reliability of our research focus—an attentional oblique effect in simultaneity judgments—by direct replication, three times. The first replication of Experiment 1a was based on an independent sample of 17 naive participants, described below in Experiment 1b. The second and third replications of Experiment 1a were based, respectively, on independent samples of 22 and 17 naive participants, described below in Experiments 2a and 2b.

Results and discussion

The results from Experiment 1a are shown in Figure 3. When the displays contained only two Gabor stimuli, simultaneity judgments ($d'$) were statistically indistinguishable across the horizontal, vertical, and diagonal attentional conditions (Figure 3, left panel, left cluster: $F(2,34) = 1.447$, $p = 0.249$, $P \eta^2 = 0.078$, n.s.). The slight $d'$ reduction in the 2-Gabor diagonal condition was not owing to false alarms, which were virtually identical across the horizontal, vertical, and diagonal attentional conditions (Figure 3, center panel, dark bars: $F(2,34) = 0.009$, $p = 0.991$, $P \eta^2 = 0.001$, n.s.). Instead, the slight $d'$ reduction in the 2-Gabor diagonal condition arose because the miss rate was non-significantly higher diagonally than horizontally or vertically (Figure 3, right panel, dark bars: $F(2,34) = 1.817$, $p = 0.178$, $P \eta^2 = 0.097$, n.s.).

The results from the 2-Gabor condition contrast sharply and qualitatively from those in our standard 4-Gabor condition (Figure 3, left panel, right cluster), where simultaneity judgments ($d'$) were significantly worse for diagonally attended targets than for either horizontally ($t(40) = 2.770$, $p = 0.013$, $P \eta^2 = 0.311$) or vertically ($t(40) = 2.543$, $p = 0.021$, $P \eta^2 = 0.276$) attended targets. This anisotropy in $d'$ arose primarily from false alarms (Figure 3, center panel, light bars), which were significantly greater when participants attended diagonally than when attending horizontally ($t(40) = 2.181$, $p = 0.043$, $P \eta^2 = 0.219$). Miss rates did not fluctuate significantly when participants attended horizontally, vertically, or diagonally in the standard 4-Gabor condition (Figure 3, right panel, light bars: $F(2,34) = 1.653$, $p = 0.206$, $P \eta^2 = 0.089$, n.s.).
Overall, the pattern of errors and absence of a significant oblique effect in the 2-Gabor condition argue against the possibility that the oblique effect in the standard 4-Gabor condition reflects an intrinsic anisotropy—fewer or weaker physiological connections among diagonally offset retinotopic locations. Indeed, a significant oblique effect was obtained only when two distractor Gabor stimuli had to be excluded from the simultaneity judgment. Excluding irrelevant stimuli is a hallmark of attentional selection. Thus, Figure 3 confirms an oblique effect in attentional selection and disconfirms the role of intrinsic (“bottom-up”) influences in the anisotropy observed here.

As noted in the Introduction section, our SDT-based error analysis (Figure 3, center and right panels) provides information about the cause of the attentional oblique effect. The observation that the attentional oblique effect was significant for false alarms confirms the possibility that the anisotropy arose from inappropriately integrating (failing to exclude) the temporal variations from distractor locations. By contrast, the absence of a significant attentional oblique effect in the miss rate disconfirms the possibility that the anisotropy reflects lower temporal acuity when attending diagonally. It also argues against greater overall noise when attending obliquely, which would have elevated both the oblique false alarm rate and the oblique miss rate.

In principle, Experiment 1a could have revealed a laterality effect. A laterality effect would have been evident to the extent that the horizontal and diagonal (bilateral) conditions had been similar to each other but different from the vertical (unilateral) condition. This was not the case. Instead, the data from Experiment 1a confirmed greater similarity between the horizontal (bilateral) and vertical (unilateral) conditions than between the horizontal and diagonal (bilateral) conditions: an oblique effect, not a laterality effect. That laterality did not influence attention on our simultaneity task is intriguing because laterality has been shown to influence numerous other visual attention tasks (Alvarez & Cavanagh, 2005; Awh & Pashler, 2000; Chakravarthi & Cavanagh, 2009a; Ludwig, Jeeves, Norman, & DeWitt, 1993; Reardon, Kelly, & Matthews, 2009; Sereno & Kosslyn, 1991). We explored another visual attention task—spatial frequency discrimination—in Experiments 2a and 2b.

Before addressing spatial frequency discrimination, we turn first to Experiment 1b, where we investigated whether the attentional oblique effect in simultaneity judgments observed across lateral hemifields in Experiment 1a also occurs within lateral hemifields. Additionally, Experiment 1b controlled for the possibility that the oblique effect observed in Experiment 1a was caused by either or both of two stimulus confounds. The first was the distance between the discriminanda, which was ~41.42% greater in the diagonal condition than in either the horizontal or vertical conditions per the Pythagorean Theorem. The second was collinearity: the fixation point was collinear with the discriminanda in the diagonal condition but not the horizontal or vertical conditions. Interestingly, prior work suggests an attentional advantage for collinear stimuli (Crundall, Cole, & Galpin, 2007), unlike the deficit observed in Experiment 1a’s collinear (diagonal) condition. Nevertheless, we controlled for the collinearity confound in Experiment 1b.

**Experiment 1b: Simultaneity judgments within hemifields**

**Methods**

**Stimuli**

Figure 4 schematizes the stimuli in Experiment 1b. On each trial, the display contained six Gabor stimuli, and a fixation letter laterally displaced 11.625 deg from the display’s center. The fixation letter’s lateral displacement rendered all six Gabor stimuli entirely within the left hemifield (Figure 4, left panel) or entirely within the right hemifield (Figure 4, right panel). The center of each of the six Gabor stimuli was positioned on an imaginary circle, 23.25 deg in diameter. This was the center-to-center distance between the two Gabor stimuli in each diagonally aligned pair and between the two Gabor stimuli in the new vertical, “center” pair. This new center pair, therefore, served as a distance control for the diagonal condition, while having component Gabor stimuli that were vertically rather than diagonally aligned. The two other vertically aligned pairs—the “near vertical” and the “distant vertical” pairs relative to fixation—each contained Gabor stimuli vertically separated by 16.44 deg center to center. The near vertical and distant vertical conditions comprised the same constituent retinal locations as the diagonal condition.
thereby serving as a control for retinal location while differing from the diagonal condition in angle of alignment. Importantly, the mean distance from fixation to the midpoint between the targets was identical (11.625 deg) across the diagonal, center, and (combined near and distant) vertical conditions. Moreover, none of the stimulus conditions in Experiment 1b comprised discriminanda that were collinear with fixation, unlike the diagonal (but not horizontal or vertical) condition in Experiment 1a. In short, the stimulus conditions in Experiment 1b controlled for distance and collinearity confounds within each lateral hemifield.

Task and participants
As in Experiment 1a, the participant was first required to correctly identify the fixation letter—now displaced to a laterally cued position. If the letter response was correct, the participant judged peripheral simultaneity, i.e., indicated whether the two cued peripheral Gabor targets changed orientation at the same time or at different times. Seventeen new naive Denison University undergraduates completed Experiment 1b.

Procedure
All participants successfully completed practice trials similar to those for Experiment 1a but with the stimuli shown in Figure 4. Subsequently, each participant completed 360 actual trials. These comprised four 90-trial blocks—two for attending to the left visual field (while fixating to the right) and two for attending to the right visual field (while fixating to the left). The four 90-trial blocks were completed in either an ABBA or a BAAB sequence randomly assigned to each participant. Each 90-trial block comprised three randomly ordered 30-trial blocks, segregating the diagonal, center, and vertical conditions. The vertical condition comprised one 30-trial block each of the "near vertical" and "distant vertical" pairings, within each lateral hemifield condition. In all other ways, the procedure was the same as in Experiment 1a.

Results and discussion
Evidence that the attentional oblique effect for simultaneity judgments occurs within a lateral hemifield can be seen in Figure 5. Here, the data obtained exclusively from within the left hemifield are combined with those obtained exclusively from within the right hemifield. The left panel of Figure 5 shows that simultaneity judgments ($d'$) were significantly worse in the diagonal condition than in either the vertical ($t(16) = 6.966, p < 0.001, P_{\eta^2} = 0.752$) or center ($t(16) = 2.226, p = 0.041, P_{\eta^2} = 0.236$) conditions. This anisotropy in $d'$ arose mostly from false alarms (center panel), which were significantly greater in the diagonal condition than in either the vertical ($t(16) = 3.673, p = 0.002, P_{\eta^2} = 0.458$) or center ($t(16) = 5.326, p < 0.001, P_{\eta^2} = 0.639$) condition. By contrast, there was no evidence for a significant oblique effect in the miss rate (right panel). Indeed, visual inspection of Figure 5 reveals a lower miss rate in the vertical condition than in the center or diagonal condition—a pattern consistent with a distance effect, not an oblique effect.

Figure 6 replots the data from Figure 5, disaggregated into separate data clusters for the left and right hemifields. When participants attended the left hemifield (while fixating a letter on the right of the display), false alarms in the diagonal condition significantly exceeded those in either the vertical ($t(16) = 3.407, p = 0.004, P_{\eta^2} = 0.420$) or center ($t(16) = 4.410, p < 0.001, P_{\eta^2} = 0.549$) condition (left panel, left cluster). Similarly, when participants attended the right hemifield (while fixating a letter on the left of the display), false alarms in the diagonal condition significantly exceeded those in either the vertical ($t(16) = 2.440, p = 0.027, P_{\eta^2} = 0.271$) or center ($t(16) = 3.761,
Sharply contrasting with these significant oblique effects in false alarms, the miss rate exhibited no significant evidence for an oblique effect when participants attended either the left (right panel, left cluster) or right hemifield (right panel, right cluster). Indeed, Figure 6 reveals that the miss rate within each hemifield was lower in the vertical condition than in the center or diagonal condition—a pattern consistent with a distance effect, not an oblique effect.

Thus, the within-hemifield data (Figures 5 and 6) show a similar pattern as the between-hemifield data (Figure 3). That is, they show an attentional oblique effect when judging simultaneity that originates more from an anisotropy in false alarms than from an anisotropy in misses. In turn, this pattern of errors confirms the possibility that both within and across hemifields, the attentional oblique effect in simultaneity judgments reflects inappropriate spatial integration of temporal asynchronies from distractor locations. By contrast, the absence of a significant attentional oblique effect in the miss rate disconfirms the possibility that the anisotropy reflects lower temporal acuity when attending diagonally. It also argues against greater overall noise in the oblique condition, which would have elevated both the oblique false alarm rate and the oblique miss rate.

Figures 5 and 6 also disconfirm that the attentional oblique effect in simultaneity judgments is an artifact of the distance between discriminanda and/or collinearity with fixation. Collinearity and distance confounds—though present in Experiment 1a—were controlled with Experiment 1b’s center condition, which generated significantly lower $d'$ values and false alarm rates than the diagonal condition did. The issue of distance and collinearity confounds across hemifields will be addressed in Experiment 2b.

Lastly, we note that a significant attentional oblique effect was obtained within each hemifield even though overall performance levels differed significantly when attending to the left versus right hemifield. As is visually apparent in the right panel of Figure 6, miss rates when attending the right hemifield significantly exceeded those when attending the left hemifield ($t(16) = 4.205, p < 0.001, \eta^2 = 0.525$). In contrast to the miss rates, the false alarm rates (Figure 6, left panel) were only non-significantly greater when attending the right hemifield versus the left hemifield ($t(16) = 1.537, p = 0.144, \eta^2 = 0.129$). This error analysis reveals an intriguing difference between the left visual field superiority effect and the attentional oblique effect. Specifically, the attentional oblique effect arose from an anisotropy in false alarms, perhaps reflecting inappropriately integrated distractor asynchronies. This is unlike the left visual field superiority effect, which arose mostly from an elevated miss rate, perhaps reflecting greater temporal precision in the neural response to temporal asynchronies located in the left (versus right) visual hemifield. We will further consider this left hemifield advantage in the General discussion section.

Experiment 2a: Simultaneity and spatial frequency

Experiment 2a was conducted to directly compare the error patterns that arise when attending to the temporal versus the spatial features of the same stimulus. One would expect the oblique effect for temporal features to be paralleled for spatial features to the extent that these two different types of feature attention are critically limited by shared neural events.

The SDT-based interpretation of errors on our spatial task parallels that described in the Introduction section for our temporal task. On our spatial task, a “miss” occurs when a participant fails to report a spatial frequency difference that is present in the targets. A “false alarm” occurs when a participant reports a difference that is not present in the targets’ spatial frequency. As before, the pattern of misses and false alarms can be informative. Specifically,
one would expect both more misses and more false alarms for obliquely versus cardinally attended targets if the attentional oblique effect simply reflected increased neural noise. By contrast, one would expect more oblique than cardinal misses, but no difference in false alarms, if the attentional oblique effect reflects low spatial acuity. Conversely, one would expect more oblique than cardinal false alarms, but no difference in misses, if the attentional oblique effect reflects a failure to exclude spatial frequency differences from distractors, i.e., inappropriate spatial integration.3

Methods

Stimuli

The stimuli in Experiment 2a were identical to Experiment 1a’s standard 4-Gabor stimuli (Figure 1) in all ways except spatial frequency. Here, each peripheral Gabor stimulus—whether target or distractor—was assigned either of two spatial frequencies. These were 1.25 cycles per degree (as in Experiment 1a) and one of six spatial frequencies lower than 1.25 cycles per degree by either 8%, 12%, 16%, 20%, 24%, or 28%. The procedure for determining the lower spatial frequency is described below.

Task

Experiment 2a comprised the same central letter task as in Experiment 1a and two peripheral tasks. One was the same simultaneity task as in Experiment 1a. The other required participants to judge the two Gabor targets to be the same or different in spatial frequency.

Participants and procedure

Twenty-two new naive Denison University undergraduates completed Experiment 2a. Each participant completed the experiment in two separate daily sessions. The first daily session was simply for range finding. The range-finding session began with practice trials followed by 180 simultaneity-task trials used for analysis, all according to the procedure described in Experiment 1a. Over the remaining 180 trials, we used the following procedure for avoiding floor and ceiling effects on the spatial frequency task. The spatial frequency difference between targets was initially set to 24% for each participant and was reevaluated every 90 trials (three 30-trial blocks, separately representing the horizontal, vertical, and diagonal attentional conditions), while participants took a 30-s break. At each reevaluation point, if the participant’s spatial frequency judgments exceeded 80% correct, the spatial frequency difference was decreased by an additional 8% of the initial 1.25 cpd value—until reaching our 8% minimum difference. If the participant’s spatial frequency judgments were less than 65% correct, the spatial frequency difference was increased by an additional 4% of the initial 1.25 cpd value—until reaching our 28% maximum difference. The temporal and spatial parameters estimated for each participant during the range-finding session were used during the second daily session.

The second daily session began with ten warm-up trials on each task followed by 360 actual trials, which were separated into 30-trial blocks. Each 30-trial block addressed a single task (simultaneity or spatial frequency) and a single target-quadrant pair (top, bottom, left, right, diagonal up, or diagonal down). The blocks were counterbalanced for each participant to eliminate order effects across tasks and attentional conditions (horizontal, vertical, or diagonal). Critically, for a given participant, the visual stimulation was identical across all experimental conditions.

Results and discussion

The left panel of Figure 7A shows our second replication of the attentional oblique effect when judging simultaneity. As in Experiments 1a and 1b, simultaneity judgments (d’) in Experiment 2a were significantly lower in the diagonal condition than in either the horizontal (t(1,21) = 3.830, p < 0.001, Pη² = 0.411) or vertical (t(1,21) = 4.077, p < 0.001, Pη² = 0.442) condition. The right panel of Figure 7A indicates that the attentional oblique effect was less evident for spatial frequency discrimination. Specifically, relative to the diagonal condition, spatial frequency discrimination (d’) was significantly greater in the horizontal condition (t(1,21) = 2.697, p = 0.013, Pη² = 0.257) but not in the vertical condition.

There were also important qualitative differences between the errors made on the two tasks. This can be seen in Figure 7B, which replots the data from Figure 7A separately for false alarms (left panel) and misses (right panel). As was true for participants in Experiments 1a and 1b, participants in Experiment 2a generated significantly more false alarms on the simultaneity task when attending diagonally than when attending horizontally (t(1,21) = 2.205, p = 0.039, Pη² = 0.188) or vertically (t(1,21) = 2.973, p = 0.007, Pη² = 0.296; left panel, left cluster). By contrast, false alarm rates were virtually identical across the horizontal, vertical, and diagonal conditions on the spatial frequency task (left panel, right cluster). This task-specific pattern of false alarms disconfirms that the two tasks are governed by the same spatial integration rules. Irrelevant information from non-cued locations appears to be integrated when attending to simultaneity but not when attending to spatial frequency—even after holding stimulation identical across these two tasks.

Comparing the left and right panels of Figure 7B reveals that the oblique effect on the spatial frequency task was driven only by the miss rate. Relative to the diagonal condition, the spatial frequency miss rate (right panel, right cluster) was significantly lower in the horizontal condition (t(1,21) = 4.078, p < 0.001, Pη² = 0.442) and marginally significantly lower in the vertical condition (t(1,21) = 1.98,
The oblique effect on the simultaneity task was less consistent in the miss rate (right panel, left cluster), which was significantly lower in the vertical ($t(1,21) = 2.523, p = 0.020, \eta^2 = 0.233$) but not horizontal condition, relative to the diagonal condition. In short, Figure 7B reveals qualitatively different error patterns on the two tasks.

Experiment 2b: Distance and collinearity controls

Although Experiments 1a and 2a each provided evidence for an attentional oblique effect across hemifields, the same pattern of data could have been caused by either or both of two stimulus confounds, the distance between discriminanda and/or collinearity with fixation. In Experiment 1b, we ruled out both of those confounds for the within-hemifield case. An earlier study indicated that when two attended targets are in opposite lateral hemifields—as in our diagonal and horizontal conditions—performance is unaffected by inter-target distance (Kraft et al., 2005). Similarly, studies addressing the temporal discrimination of widely spaced targets indicate that temporal sensitivity remains relatively unchanged with increasing spatial separation (Aghdaee & Cavanagh, 2007; Forte, Hogben, & Ross, 1999). Nevertheless, we controlled for both the distance confound and the collinearity confound in Experiment 2b. Additionally, Experiment 2b provided a fourth sample in which to confirm or disconfirm an attentional oblique effect on simultaneity judgments and a second sample for testing attention to spatial frequency.

Figure 7B. Error analysis from Experiment 2a. (Left) False alarm rates exhibited an oblique effect on the simultaneity task but not the spatial frequency task, raising the possibility of different spatial integration rules for the two tasks. (Right) An oblique effect on the spatial frequency task was evident only in the miss rate.
Methods

Stimuli and task

The stimuli in Experiment 2b were identical to those in Experiment 2a except for replacement of the “vertical” condition with a new “center” condition, schematized in Figure 8. The center condition comprised two additional peripheral Gabor stimuli horizontally aligned with fixation and separated (center to center) 32.4 deg from each other. As all our other Gabor stimuli, the Gabor stimuli in the center condition were each centered 16.2 deg from fixation. Critically, the new center condition matched the diagonal condition in collinearity with fixation and inter-target distance. The tasks remained identical to those in Experiment 2a.

Participants and procedure

Seventeen new naive Denison University undergraduates completed Experiment 2b, which was conducted across two daily sessions. The procedures for the two daily sessions were identical to those described for Experiment 2a, with one exception. Now, the center attentional condition (Figure 8) replaced the vertical attentional conditions (left and right target-quadrant pairs) from Experiment 2a. Again for each participant, the retinal stimulation was identical across the tasks and attentional conditions in Experiment 2b.

Results and discussion

The left panel of Figure 9A displays our third replication of the attentional oblique effect when judging simultaneity. As in Experiments 1a, 1b, and 2a, simultaneity judgments \((d')\) were significantly lower in the diagonal condition than in either the horizontal \((t(1,16) = 5.300, p < 0.001, \eta^2 = 0.637)\) or center \((t(1,16) = 3.250, p = 0.005, \eta^2 = 0.398)\) condition. The significant difference between the diagonal and center conditions cannot be attributed to collinearity differences or to different distances between the discriminanda. Instead, the data implicate the oblique angle, *per se*, for simultaneity judgments.

Interestingly, the same sample of participants under the same retinal stimulation did *not* demonstrate an oblique effect in spatial frequency discrimination. As is visually apparent in the right panel of Figure 9A, this sample’s spatial frequency discrimination \((d')\) was virtually identical across the horizontal, center, and diagonal conditions \((F(1,16) = 0.485, p = 0.792, \eta^2 = 0.014)\).

There were also important *qualitative* differences between the errors made on the two tasks. This can be seen in Figure 9B, which replots the data from Figure 9A separately for false alarms (left panel) and misses (right panel). As was true for participants in Experiments 1a, 1b, and 2a,
participants in Experiment 2b generated significantly more false alarms on the simultaneity task in the diagonal attention condition than in the horizontal ($t(1,16) = 2.650, p = 0.017, P^2 = 0.305$) or center attention condition ($t(1,16) = 2.871, p = 0.011, P^2 = 0.340$; left panel, left cluster). By contrast, false alarm rates were statistically indistinguishable across the horizontal, vertical, and diagonal conditions on the spatial frequency task (left panel, right cluster). This task-specific pattern of false alarms disconfirms that these two different types of feature attention are critically limited by shared neural events, even under identical stimulation.

Comparing the right clusters of the left and right panels of Figure 9B reveals that significant oblique effects on the spatial frequency task occurred only in the miss rate. Relative to the diagonal condition, the spatial frequency miss rate (right panel, right cluster) was significantly lower in the horizontal condition ($t(1,16) = 4.275, p = 0.001, P^2 = 0.533$) and significantly lower in the center condition ($t(1,16) = 4.536, p < 0.001, P^2 = 0.563$) but not center condition, relative to the diagonal condition. This miss rate pattern on the simultaneity task, like that in Experiment 1b, is more consistent with a distance effect than with an oblique effect. Overall, Figure 9B reveals different error patterns on the two tasks, particularly in the false alarm rate.

Study-wide summary of attentional oblique effects

Table 1 summarizes the magnitude of the attentional oblique effects observed in the four independent samples tested here. Each value reflects the sensitivity loss when attending obliquely, expressed as the percent reduction in

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Simultaneity 2-Gabor</th>
<th>Simultaneity 4-Gabor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>9.68%</td>
<td>29.40%</td>
</tr>
<tr>
<td>Horizontal</td>
<td>9.11</td>
<td>29.70%</td>
</tr>
<tr>
<td><em>Center</em></td>
<td>13.96%</td>
<td>11.93%</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Simultaneity 6-Gabor: Left VF</th>
<th>Simultaneity 6-Gabor: Right VF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>20.15%</td>
<td>22.63%</td>
</tr>
<tr>
<td><em>Center</em></td>
<td>13.96%</td>
<td>11.93%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Simultaneity 4-Gabor</th>
<th>Spatial frequency 4-Gabor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td>26.30%</td>
<td>14.88%</td>
</tr>
<tr>
<td>Horizontal</td>
<td>20.42%</td>
<td>22.00%</td>
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</table>

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Simultaneity 6-Gabor</th>
<th>Spatial frequency 6-Gabor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal</td>
<td>35.89%</td>
<td>5.73%</td>
</tr>
<tr>
<td><em>Center</em></td>
<td>24.76%</td>
<td>5.67%</td>
</tr>
</tbody>
</table>

Table 1. Attentional oblique effect summary. Values reflect the percent reduction in sensitivity ($d'$) when attending obliquely, compared to the cardinal attention condition in the left column. Reductions occurred in all conditions.
General discussion

The present study extended the investigation of the oblique effect in two novel ways: from stimulus-driven vision to visual attention and from space to time. Specifically, we investigated the ability to attend to the simultaneity of temporally varying targets presented among temporally varying distractors. The experiments generated two main findings. First, false alarms in simultaneity judgments were significantly lower when participants attended to temporally varying targets presented in the left column. Oblique sensitivity losses ranged between 5.67% (when attending obliquely to spatial frequency) and 35.89% (when attending obliquely to simultaneity) and occurred in 16 of 16 experimental conditions (binomial $p < 0.0001$).

Our results point to the failure to exclude the distractors’ temporal properties as the most likely cause of the oblique effect observed in each of the four independent samples tested here. First, across and within hemifields, simultaneity judgments exhibited an oblique effect in false alarms, i.e., an instance of inappropriate spatial integration.

Might inappropriate spatial integration in the present study be an instance of crowding? After all, Pelli, Palomares, and Majaj (2004) state that crowding occurs when “features are integrated over an inappropriately large area because there are no smaller integration fields—so the integrated signal is ambiguous” (p. 1136). However, as noted in the Methods section, our target–distractor displacement far exceeded the critical region for crowding (Toet & Levi, 1992). Therefore, crowding is an unlikely explanation for the present attentional oblique effect.

In addition to an attentional oblique effect, our SDT-based error analysis also revealed an attentional asymmetry in temporal acuity via the miss rates. On the simultaneity task in Experiment 1b, miss rates were significantly lower when participants attended to temporal asynchronies in the left (versus right) hemifield. That is, there was a left visual field advantage in the temporal acuity of attention. This corroborates the left visual field advantage on a rapid serial visual presentation (RSVP) task recently reported by Verleger et al. (2009). Their EEG data also revealed a corresponding right hemisphere advantage in individuating the targets temporally. Indeed, the right parietal lobe’s importance in temporal judgments has been documented by experimental manipulations involving transcranial magnetic stimulation (Müri et al., 2002; Woo, Kim, & Lee, 2009) and by clinical reports of split brain (Forster, Corballis, & Corballis, 2000) and right parietal lobe patients (Battelli et al., 2001; Battelli, Cavanagh, Martini, & Barton, 2003; Rorden, Mattingley, Karnath, & Driver, 1997). These findings have led to recent speculation about a “when” pathway (Battelli, Pascual-Leone, & Cavanagh, 2007; Battelli, Walsh, Pascual-Leone, & Cavanagh, 2008; Davis, Christie, & Rorden, 2009) that is distinct from the “what” (ventral) and “where” (dorsal) pathways (Mishkin & Ungerleider, 1982).

The present simultaneity data also corroborate Verleger et al.’s (2009) RSVP study in another way. On their RSVP task—an alternative measure of attention’s temporal precision—the lag between the targets to be detected is spanned from 107 to 535 ms. Those durations are in a range comparable to the 100- to 300-ms asynchronies tested on the present simultaneity task. Similarly, estimates in the ~100- to ~250-ms (10 to 4 Hz) range have been observed for attention’s temporal resolution when participants discriminated the phase of two flickering stimuli (Aghdaee & Cavanagh, 2007; Rogers-Ramachandran & Ramachandran, 1998). It would not have to be the case that these separate measures (simultaneity, RSVP, phase-flicker discrimination) of attention’s temporal precision would converge to comparable quantitative estimates—the low hundreds of milliseconds. In principle, a measurement based on just two samples, e.g., a simultaneity measurement, could exhibit hyperacuity performance levels (DeValois & DeValois, 2011)
Despite this possibility, we are unaware of hyperacuities reported for attention's temporal grain. We are also not aware of prior studies reporting an attentional oblique effect. Such an effect is not implausible, however, given the considerable prior evidence that visual attention is not homogenous across the visual field. For example, it has been argued that attention influences crowding (Chakravarthi & Cavanagh, 2007, 2009a, 2009b; but see Freeman & Pelli, 2007)—and the critical region for crowding varies across the visual field. Indeed, crowding's critical region extends further along the radial than tangential axis to fixation (Feng, Jiang, & He, 2007; Toet & Levi, 1992) and is not homogeneous within and across lateral hemifields (Chakravarthi & Cavanagh, 2009a; Liu, Jiang, Sun, & He, 2009). Additionally, attentional performance is often better in the lower than upper visual field (Carrasco, Giordano, & McElree, 2004; He, Cavanagh, & Intrilligator, 1996; McAnany & Levine, 2007; Montaser-Kouhsari & Carrasco, 2009; Rubin, Nakayama, & Shapley, 1996). He et al. (1996) suggested that this lower field advantage could arise in the parietal lobe, an attention-related region (Buschman & Miller, 2007) that receives more projections corresponding to the lower than the upper visual field (Van Essen, Newsome, & Maunsell, 1984). A conceptually similar argument—an overrepresentation of cardinal-tuned neurons in the primary visual cortex (Li et al., 2003; Mansfield, 1974)—is traditionally offered to explain the oblique effect in stimulus-driven vision.

**Conclusion**

The attentional oblique effect reported here for simultaneity judgments is intriguing for two reasons. First, simultaneity judgments are a prima facie temporal measure. Given this, one might have guessed that an oblique effect in simultaneity would reflect an anisotropy in temporal acuity, not spatial integration. Counterintuitively, the pattern of errors observed here is more consistent with the latter than with the former. Second, the present oblique effect in false alarms was eliminated when participants attended to spatial frequency rather than to simultaneity, despite identical retinal stimulation on the two tasks. These task-specific error patterns raise the possibility of different spatial integration windows when attending to spatial versus temporal features, even when those features are co-presented in space and time.

**Acknowledgments**

We thank Drs. Marisa Carrasco and Jeremy Wolfe for their helpful comments about how to control the distance confound in the diagonal attention condition. Additionally, we thank our anonymous reviewers for suggesting the 2-Gabor condition in Experiment 1a and the within-hemifield vertical distance control in Experiment 1b.

**Footnotes**

1Toet and Levi (1992) found that spatial crowding occurs when the center-to-center distance between targets and distractors is 0.25 times the target eccentricity in the tangential direction and 0.5 times the target eccentricity in the radial direction. Our targets were centered 16.2 deg diagonally from fixation, rendering target–distractor critical spacings of 4.05 and 8.1 deg along the tangential and radial directions, respectively.

2In all experiments reported here, the accuracy of the initial letter response for each participant far exceeded the chance performance level of 10% correct. Additionally, within each experimental condition, the mean accuracy of the initial letter response always exceeded 86% correct and usually exceeded 90% correct.

The phrase “low spatial acuity” refers to a reduced ability to discriminate spatial frequencies. This is not to be confused with the phrase “inappropriate spatial integration,” which refers to a reduced ability to exclude features from task-irrelevant locations. Low spatial acuity and inappropriate spatial integration are distinct phenomena.

The “center” condition in Experiment 2b comprised horizontally aligned stimuli, unlike the vertically aligned “center” condition in Experiment 1b.

**References**


