Conjunction benefits and costs reveal decision priming for first-order and second-order features

LISA R. FOURNIER AND ROBERT PATTERSON
Washington State University, Pullman, Washington

BRIAN P. DYRE
University of Idaho, Moscow, Idaho

AND

MATTHEW WIEDIGER AND RYAN WINTERS
Washington State University, Pullman, Washington

Across two experiments, decision priming was examined for conjunctions composed of first-order or first- and second-order stimulus features. Observers indicated the presence or absence of one or two features in a Gabor stimulus. When a pair of stimulus features differed in their speed of discrimination, responses indicating the presence of a conjunction were faster than those for the single feature for which discrimination was slowest (conjunction benefits). Also, responses indicating the absence of a conjunction were delayed if one of the features was present (conjunction costs). These results show that first- and second-order features can prime decisions about the presence of a conjunction and suggest that the two kinds of signals can be combined at a decision stage after the discrimination of stimulus properties has begun for each system.

Comparing decisions based on target stimuli defined by multiple features and those defined by single features has played an essential role in the development of many selective attention models (e.g., Bundesen, 2002; Cave, 1999; Cohen & Shoup, 2000; Duncan, 1984, 1996; Lavie, 1995; Treisman & Gelade, 1980; Treisman & Sato, 1990; Wolfe, 1994). Evidence indicating differences in selection times and attentional capacity demands between multiple- and single-feature targets has typically been based on reaction time (RT) and accuracy measures. However, the question of how differences in discriminability and response mappings among features within these targets affect discrimination time and accuracy has been generally ignored. Furthermore, it is not known whether such differences affect targets composed of first-order features (defined by differences in mean luminance) and those composed of both first-order and second-order features (e.g., defined by contrast modulation without a change in mean luminance) similarly. Investigation of these factors can provide insight into how different classes of stimulus features are combined to render a decision concerning the presence or absence of a visual stimulus.

Fournier and colleagues recently showed that the speed with which one can accurately determine the presence or absence of a target defined by multiple first-order features is dependent on the discrimination speed and response mapping of features on the task-relevant stimulus dimensions

(Fournier, Bowd, & Herbert, 2000; Fournier, Eriksen, & Bowd, 1998; Fournier, Herbert, & Farris, 2004; Fournier, Scheffers, Coles, Adamson, & Abad, 2000). They had observers judge the presence or absence of one or two target features within an object at a fixed and known spatial location. For example, the object was a letter that varied in hue (red or green) and shape (H or K) with the physical characteristics of the stimuli (e.g., size), making the shape of the letters slower to discriminate than their hue. They found that responses indicating the presence of the conjunction *red X* were faster than responses indicating the presence of the shape *X* alone. Thus, identifying whether two features are present in a stimulus can be faster than identifying whether the single feature, for which discrimination is slowest, is present. This faster response to the presence of a conjunction is called a *conjunction benefit*. In addition, they found that responses indicating the absence of a conjunction *red X* were faster than responses indicating the absence of the shape *X* alone, but only when all of the target features were absent in the former case. If one of the target features was present, responses indicating the absence of a conjunction were much slower, as compared with the case in which neither of the target features were present. These absent responses were particularly slow when the feature that was discriminated faster was the feature that was present (e.g., red). Slower responses indicating the absence of a conjunction when one of the target features is present is called a *conjunction cost*.

L. R. Fournier, fournier@wsunix.wsu.edu

Both conjunction benefits and costs were accounted for by decision priming; that is, the feature that is discriminated more quickly can partially activate (prime) a central decision stage corresponding to the presence or absence of a target conjunction (Fournier, Scheffers, et al., 2000; Fournier et al., 2004). For example, when the target conjunction is *red X* and the stimulus presented is a *red X*, separate decision processes occur in a parallel, continuous fashion, reflecting whether each stimulus feature on the task-relevant dimensions (hue or shape) is present or absent in the conjunction target. If hue is discriminated more quickly than shape, the accumulating activation indicating the presence of the red hue can partially activate (prime) the decision, at a central decision stage, about the presence of the conjunction held in memory before the *X* shape. Shortly afterward, the accumulating activation indicating the presence of the *X* shape will also contribute to this decision about the presence of the conjunction and will be temporally integrated with the decision activation that has already been accumulating from the red hue. In turn, the early decision activation (priming) at the central decision stage indicating the presence of the red *X* conjunction by the red hue will boost the growth rate of the incoming information indicating the presence of this conjunction by the *X* shape because it is consistent with this early decision information (e.g., Flowers & Wilcox, 1982; Grice, Boroughs, & Canham, 1984; James, Humphrey, Gati, Menon, & Goodale, 2000). That is, the growth rate of the more slowly processed feature will increase (peak sooner without a change in amplitude; see, e.g., James et al., 2000) through feedback based on priming from the higher level decision stage. Thus, as the accumulating activation of the two features is temporally integrated, the criterion indicating that the conjunction is present can be reached earlier, relative to that for the single-feature target for which discrimination is slowest and can lead to a conjunction benefit.¹ If, however, the stimulus *red O* is presented and the feature analyzers indicate that one feature is present (e.g., red) and the other is absent (e.g., not shape *X*), the decision about the presence of the red hue will incorrectly prime the decision that the red *X* conjunction is present. In this case, the decision activation resulting from the absence of the shape must override the primed decision that the conjunction is present (e.g., Eriksen & Schultz, 1979). This takes additional processing time, and hence, the decision threshold representing the absence of the conjunction is reached later, resulting in a conjunction cost. Importantly, the existence of conjunction costs suggests that each feature on the task-relevant dimensions is identified to the extent that each can partially activate (prime) a decision as to whether a conjunction target is present or absent *before* the composite representation of the features on the task-relevant dimensions is analyzed.

Fournier et al. (2004) showed that certain conditions are necessary for conjunction benefits and costs to occur. First, each feature on the task-relevant dimension must be consistently mapped to a response (e.g., either *present* or *absent*) so that each feature can activate its corresponding response independently. Second, responses to individual features cannot be contingent on the identification of one

or more features on the other task-relevant dimensions.² Third, for conjunction benefits to occur, each feature on the task-relevant dimensions must differ in discrimination speed to allow one feature to prime the decision corresponding to the target conjunction. Discrimination speed of features between task-relevant dimensions is manipulated by having observers discriminate differences from narrowly or widely separated points along a given stimulus dimension; large differences between target features make this decision process faster. If features across task-relevant dimensions are similar in discrimination speed, responses corresponding to the presence of a conjunction will be similar in speed to those corresponding to the presence of the single features judged in isolation.

Feature conjunction benefits and costs have been shown to occur for both two- and three-feature targets across first-order dimensions, such as nonisoluminant color, shape, size, and orientation (Fournier, Bowd, & Herbert, 2000; Fournier et al., 1998; Fournier et al., 2004; Fournier, Scheffers, et al., 2000). They have occurred for objects present among distractors, as well as for objects presented alone (Fournier, Bowd, & Herbert, 2000; Fournier et al., 2004; Fournier, Scheffers, et al., 2000). In all of these cases, displays were physically identical between the multiple-feature and the single-feature targets. Also, several factors have been eliminated as playing a significant role in feature conjunction benefits, such as differences in memory demands, attentional demands, feature uncertainty, or target feature expectancies (Fournier et al., 1998; Fournier et al., 2004). Because response mapping of individual features plays a key role in conjunction benefits and costs, Fournier et al. (2004) concluded that conjunction benefits and costs must result from decision-based processes, as opposed to a low-level feature analysis or a feature integration stage of processing that precedes decision activation of the conjunction representation (see also the ERP evidence by Fournier, Scheffers, et al., 2000).

The phenomena of conjunction benefits and costs are important for several reasons. First, they indicate that making decisions about the occurrence of a target composed of multiple features is not necessarily limited by the feature for which discrimination is slowest, in contrast to previous findings (e.g., Duncan, 1980; Hawkins, 1969; Woods, Alain, & Ogawa, 1998) or the implicit and sometimes explicit assumption by many feature integration theories that features must first be integrated by attention and only the integrated object representation can activate a decision (e.g., Cave, 1999; Lavie, 1995; Treisman & Gelade, 1980; Treisman & Sato, 1990; Wolfe, 1994; for an exception, see Cohen & Shoup, 1997). On the latter point, Fournier et al. (2004) showed that identifying whether a specific two-feature target (conjunction) is present in a cued location among distractors does not impose a greater demand on attention than do single-feature targets, which is inconsistent with evidence supporting feature integration theories that posit such a demand (e.g., Lavie, 1995). Second, conjunction benefits and costs indicate that the time taken to discriminate an object can be based on the speed with which individual features on the task-relevant dimensions making up the object are discriminated and is not necessarily based on whole-object cat-

egorization involving features on the task-irrelevant dimensions (e.g., Farrell, 1984; Ratcliff, 1978). Third, conjunction benefits and costs demonstrate that decision priming and competition can occur across different stimulus dimensions making up the same object, not just within the same dimension across different objects (Cohen & Shoup, 2000).

One issue not resolved is whether conjunction benefits and costs—that is, decision priming—can occur between first-order and second-order features. Past research, reviewed above, examined conjunction benefits and costs for first-order features that are defined by a difference in luminance or hue. The present study investigated whether conjunction benefits and costs will generalize to second-order features that are a distinct class of features defined, for example, by differences in contrast, texture, or relative motion without a change in mean luminance. There is strong evidence that the visual processing of first-order and second-order signals is fundamentally different. For example, Manahilov, Simpson, and Calvert (2005) found that the discrimination of phase of second-order patterns shows lower sampling efficiency and higher levels of additive internal noise, relative to the discrimination of phase of first-order patterns. Also, Schofield and Georgeson (2003) reported that the detection of second-order stimuli is relatively insensitive to the frequency spectrum of the noise carrier, unlike the detection of first-order stimuli. In a study involving visual evoked potentials, Calvert, Manahilov, Simpson, and Parker (2005) found that second-order stimuli evoke responses that have a longer latency than do those evoked by first-order stimuli, which were interpreted as being due, in part, to feedback connections from extrastriate areas onto primary cortex areas. In the motion domain, some research suggests that first- and second-order motion stimuli might be processed by only one mechanism (e.g., Benton, Johnston & McOwan, 1997; Johnston, McOwan, & Buxton, 1992). However, there is again strong evidence that visual processing of these stimuli is fundamentally different. For example, second-order motion, unlike that of first-order motion, does not induce optokinetic nystagmus (Harris & Smith, 1992) or a motion aftereffect with stationary test patterns (Nishida, Ashida, & Sato, 1994). Also, Smith and Ledgeway (1997) found that the direction of second-order motion, unlike that of first-order motion, cannot be discriminated at detection threshold. Furthermore, Lu and Sperling (1996) suggested that contrast gain control operates according to different principles for the two kinds of stimuli.

We were interested in whether a second-order feature, as well as a first-order feature, can prime decisions made about a conjunction composed of both first- and second-order features. To date, there has been no systematic investigation determining whether differences in discrimination time between a first-order feature and a second-order feature can influence perceptual identification of a stimulus composed of these two types of features. Also, generalizing conjunction benefits and costs to stimuli composed of both first- and second-order features has important implications concerning how these signals are combined at a decision level of processing, which has recently been questioned in the literature.

Much of the recent literature reporting investigations of the functional relationship between first-order and second-order features has suggested that these features are detected by separate early visual channels or mechanisms and their outputs are combined at some later stage of processing (e.g., Schofield & Georgeson, 1999, 2003; Smith & Scott-Samuel, 2001). In fact, some researchers (Schofield & Georgeson, 1999; Smith & Scott-Samuel, 2001) have suggested that the outputs from first-order and second-order detection mechanisms may be combined at the decision level of processing. For example, Smith and Scott-Samuel found that discrimination of the spatial frequency or speed of movement at suprathreshold levels was facilitated when first-order and second-order stimuli were combined, provided that overall contrast was low. These authors suggested that perceptual accuracy can be improved under conditions of low visibility by combining signals from the two types of stimuli at a decision stage of processing in which outputs from these hypothetically independent mechanisms are either (1) combined only after discrimination of stimulus properties occurs within each system or (2) combined prior to the operation of a single process involving discrimination of the composite stimulus (Smith & Scott-Samuel, 2001). Investigating whether conjunction benefits and costs can generalize to first-order and second-order features can directly address this question. If first-order and second-order signals can be combined at a decision stage after the discrimination of stimulus properties within each system, conjunction benefits and costs should occur when conjunctions are composed of first-order and second-order features. However, if first-order and second-order signals are combined prior to the operation of a single process involving the discrimination of the composite stimulus, feature conjunction benefits and costs should not occur when conjunctions are composed of first-order and second-order features.

In the present study, Gabor stimuli (e.g., Daugman, 1985; Marcelja, 1980)³ were used to evaluate decision priming between first- and second-order features and to determine whether feature conjunction benefits and costs will generalize to conjunctions composed of first- and second-order features. Each Gabor stimulus had a 2-D luminance distribution that was defined as the product of a carrier sinusoid and a 2-D Gaussian contrast envelope. In a typical Gabor stimulus, the sine wave is referred to as the carrier grating and is considered to be a first-order stimulus because it is defined by differences in mean luminance. The Gaussian envelope is referred to as the *contrast envelope*, and it is considered to be a second-order stimulus because it is defined by contrast modulation without a change in mean luminance. In general, processing of first-order stimuli is assumed to be done by early quasilinear filtering, whereas processing of second-order stimuli is assumed to involve nonlinear preprocessing followed by quasilinear filtering (e.g., Wilson, Ferrera, & Yo, 1992).

Feature conjunction benefits and costs were examined in two experiments. In Experiment 1, observers made judgments about the presence of two first-order target features: the spatial frequency and orientation of the sine wave carrier grating. This experiment determined whether multiple

first-order signals are combined at a decision stage after the discrimination of individual stimulus features (consistent with previous research). In Experiment 2, observers made judgments about the presence of a pair of first-order and second-order target features: the spatial frequency of the sine wave carrier grating and the orientation of the contrast envelope. This experiment determined whether first-order and second-order signals are also combined at a decision stage after the discrimination of stimulus properties has begun for each system.

GENERAL METHOD

Participants

Sixteen different undergraduates from Washington State University participated in Experiments 1 and 2. The participants had normal or corrected-to-normal acuity in each eye (assessed via a Snellen chart) and received extra credit in a psychology course for participating.

Stimuli and Apparatus

Gabor stimuli were presented on a 0.39-m-diagonal Gateway CRT display screen and were viewed through a face mask to keep viewing distance (1.65 m) constant. The screen resolution was $1,024 \times 768$ pixels (H $\times$ V), with each pixel subtending approximately 0.66×0.64 min of arc. The 2-D luminance distribution of each Gabor stimulus was defined as the product of a carrier sinusoid and a 2-D Gaussian contrast envelope, with average standard deviation (σ) equal to 0.21° . For a formal presentation of how our Gabor stimuli were created, see Tanaka and Sagi (2000). The spatial frequency of the carrier sinusoid and aspect ratio of the Gaussian envelope varied across conditions. For all stimuli, mean display luminance was 50.7 cd/m^2 and peak Michelson contrast was 99.3%.

The following procedure was used to ensure that variations in display luminance of the Gabor stimuli were indeed linear. First, gross adjustments of the video card gamma correction parameter and monitor brightness and contrast controls were used to make the luminance displayed on the two CRTs as close to linear as possible. These adjustments were guided by luminance measurements of a set of eleven 8-bit grayscale patches with values of 0, 25, 50, 75, 100, 125, 150, 175, 200, 225, and 250 units (the maximum 8-bit grayscale range is 0–255 units; luminance was measured with an International Light photometer, Model IL1400A, with SEL033 detector, R diffuser, and Y photopic filter). After these adjustments, nonlinear regression was used to estimate the parameters (a and b) of the best-fit power function [$L(G) = aG^b$] relating measured luminance values (L) to the grayscale parameters (G) for each CRT. The power function regressions accounted for 99.9% of the variability in the luminance of the displays (adjusted R^2 s $\geq .999$), and the best-fit estimates of the exponents (b) for the two displays used in these experiments were 2.29 and 2.42. The inverses of these power function exponents were then used to correct the grayscale values of our stimuli for each CRT. We confirmed this linearization by first measuring the displayed luminance of grayscale patches with software values of 0, 64, 128, 196, and 255 and linearly regressing the measured luminance on the corresponding grayscale values. For both CRTs, these linear regressions accounted for more than 99.9% of the variability in luminance measurements. Subsequently, we also measured the average luminance of the actual Gabor stimuli used in the experiments (with an aperture diameter of 2.3° of visual angle), as well as the background luminance of the displays, and found the range of mean luminance to vary less than 0.1% (0.05 cd/m^2) across the entire set of stimuli and backgrounds used.

Given that mean luminance did not vary significantly across stimuli with sinusoidal luminance variations at different orientations, we conclude that adjacent-pixel nonlinearity (APNL) was not a problem in our displays. APNL can reduce the mean luminance of

a high-frequency, high-contrast patch below its intended value and thus create a first-order luminance artifact defining the shape of the envelope (see Schofield & Georgeson, 2003). The fact that APNL was absent from our displays is not surprising, because it occurs only when there are large differences in luminance between adjacent pixels in the display. For our stimuli, the range of spatial frequencies used was 6.7–10.7 cyc/deg, which corresponded to wavelengths of 13.78–8.62 pixels per cycle, respectively. As a result, changes from the brightest to the darkest pixels occurred over a minimum of at least 4 pixels.

Even physically linear contrast-modulated sinusoids can produce visible first-order boundary artifacts, presumably due to nonlinearities in visual transduction (Scott-Samuel & Georgeson, 1999). However, these artifacts appear to be visible only at temporal frequencies higher than 4 Hz. For example, Holliday and Anderson (1994) found that cross-adaptation of first- and second-order motion can occur at temporal frequencies of ≥ 4 Hz, but not at lower temporal frequencies. With the exception of the brief period following the sudden onset of the display, our displays were static; hence, there was little or no power at nonzero temporal frequencies. Because second-order movement with stimuli containing sudden onsets and low drift rate (low temporal frequency) does not produce a measurable first-order artifact (Scott-Samuel & Georgeson, 1999), we do not believe that this artifact was significantly present in our stimuli.

Responses representing whether a target feature (or features) was present or absent were recorded by a spring-loaded hand-lever that was moved rightward or leftward by the right hand. A button held in the left hand initiated each trial.

Procedure

At the beginning of each trial, a message appeared that indicated the feature or features to be judged on that trial. The participant cleared the screen by pressing a handheld button, and then a white fixation cross (0.2° of visual angle) appeared in the center of the screen, indicating the location of the Gabor stimulus. The participant again pressed the button to initiate the onset of the Gabor stimulus, whose duration was 200 msec. The participant's task was to determine whether the target feature or features were present or absent in the Gabor stimulus. One half of the participants moved the hand-lever to the right when all target features were present and to the left when one or more target features were absent; the other half had the opposite response direction assignment. A 2-sec interval was allowed for a response, and RT and accuracy were displayed and recorded.

Stimuli were drawn from one of two stimulus sets, A or B, for a given block of trials, which alternated across blocks of trials. The relevant stimulus set, A or B, was displayed at the start of each block. The four Gabor stimuli that made up each stimulus set, as well as the type of target judgment to be performed (i.e., one- or two-feature judgment), occurred in a random order within a block of trials. All comparisons concerning whether conjunction benefits were observed were done within a given stimulus set, and not between stimulus sets.

To ensure that conjunction benefits could not be attributed to a target-feature frequency confound (Fournier et al., 1998; Nickerson, 1972, 1973), each Gabor stimulus within each stimulus set appeared equally often in each target-feature judgment condition. Note that this likely created an *absent* response bias for the two-feature targets because only one of the four Gabor stimuli in each stimulus set could match each two-feature target, whereas two of the four Gabor stimuli in each stimulus set could match each single-feature target. Thus, for the two-feature targets, a *present* response was required 25% of the time, and an *absent* response was required 75% of the time.⁴

The participants completed 2 blocks of 48 practice trials and 10 blocks of 48 experimental trials in a single 1.5-h session. Each block consisted of 32 single-feature judgments (16 judgments involving orientation and 16 judgments involving spatial frequency) and 16 two-feature judgments. Specific target features and their presence or absence occurred in a random order within each block of trials.

EXPERIMENT 1

We determined whether conjunction benefits and costs occur for first-order dimensions of carrier spatial frequency and carrier orientation and, thus, whether first-order features can prime decisions made about a conjunction composed of first-order features. In doing so, we investigated whether multiple first-order signals are combined after the discrimination of individual stimulus features, consistent with previous research.

Method

In each stimulus set, the Gabor stimuli differed across the first-order dimensions of spatial frequency and orientation of the carrier (see Figure 1), with the aspect ratio (ratio of vertical to horizontal extent) of the Gaussian envelope fixed at 0.97. The aspect ratio differed from 1.0 due to the fact that pixels were not perfectly square. In Stimulus Set A, the discrimination of spatial frequency was designed to be slower than the discrimination of orientation. Specifically, the spatial frequency of the carrier was either 6.7 or 7.7 cyc/deg, and the orientation of the carrier was either 9° to the left or 9° to the right of vertical. In Stimulus Set B, the discrimination of orientation was designed to be slower than the discrimination of spatial frequency. Specifically, the spatial frequency of the carrier was either 6.7 or 8.7 cyc/deg, and the orientation of the carrier was either 3° top tilted to the left or 3° top tilted to the right of vertical. In preliminary work, we found that features for which discrimination was faster, in terms of shorter response RTs, had an equivalent or greater degree of accuracy than did features for which discrimination was slower (see also Fournier, Bowd, & Herbert 2000; Fournier et al., 1998; Fournier, Scheffers, et al., 2000).

There were four possible single-feature judgments: low spatial frequency, high spatial frequency, top of carrier grating tilted to the left, or top of carrier grating tilted to the right. There were four possible two-feature judgments formed from different combinations of the single-feature judgments: low spatial frequency and oriented left, low spatial frequency and oriented right, high spatial frequency and oriented left, or high spatial frequency and oriented right. Throughout the experiment, each participant judged the presence or absence of a single spatial frequency, a single orientation, and one spatial-frequency–orientation combination. This means that the variable of target feature judgment (levels: spatial frequency, orientation, and spatial-frequency–orientation combination) was run as a within-subjects factor.

Results

Conjunction benefits. Figure 2 shows correct RTs and percentages of errors for *present* and *absent* responses for

each target feature across the two stimulus sets (A and B). The figure shows that conjunction benefits occurred only with Stimulus Set A; *present* responses were faster and more accurate for the two-feature target conjunction of spatial frequency and orientation than for the single-feature target of spatial frequency, for which discrimination was slowest (i.e., both *present* and *absent* response RTs were slower and response errors were greater for spatial frequency than for orientation). However, there was no conjunction benefit with Stimulus Set B, in which the speed of discrimination for spatial frequency and orientation was similar.

A repeated measures ANOVA, involving response type (present or absent), stimulus set (A or B), and target feature (spatial frequency, orientation, or spatial-frequency–orientation), was computed for mean correct RT and mean accuracy separately. With respect to correct RT, there was a significant main effect of response type [$F(1,15) = 10.72$, $p < .01$] and significant two-way interactions between response type and target feature [$F(2,30) = 4.53$, $p < .05$] and between stimulus set and target feature [$F(2,30) = 48.05$, $p < .0001$]. With regard to accuracy, there were significant main effects of stimulus set [$F(1,15) = 23.25$, $p < .001$] and target feature [$F(2,30) = 11.08$, $p < .001$], as well as significant two-way interactions between response type and stimulus set [$F(1,15) = 9.12$, $p < .01$], stimulus set and target feature [$F(2,30) = 32.97$, $p < .0001$], and response type and target feature [$F(2,30) = 4.53$, $p < .05$].

The Tukey least significant difference (LSD) test (1 and 15 degrees of freedom; $p < .05$) was used to evaluate whether mean RT and accuracy differed between the single-feature targets and whether conjunction benefits were observed for the two-feature targets in each stimulus set. For Stimulus Set A, both *present* and *absent* responses were significantly slower and less accurate for spatial frequency than for orientation ($p < .05$). Also, *present* responses were significantly faster and more accurate for the two-feature target conjunction of spatial frequency and orientation than for the single-feature target of spatial frequency ($p < .05$). For Stimulus Set B, both *present* and *absent* response RTs and accuracy were

Figure 1. Stimulus sets used in Experiment 1, in which the Gabor stimuli varied across the first-order dimensions of carrier spatial frequency and carrier orientation. The left panel shows Gabor stimuli from Stimulus Set A, and the right panel shows Gabor stimuli from Stimulus Set B.

Figure 2. Experiment 1: Mean correct reaction times (RTs) and percentages of errors for *present* and *absent* responses to the target features of carrier spatial frequency (F) and carrier orientation (O) and the conjunction of carrier spatial frequency and carrier orientation (F-O). The left panel corresponds to Stimulus Set A, and the right panel corresponds to Stimulus Set B. Error bars represent one standard error of the mean.

not significantly different between spatial frequency and orientation ($p > .05$). Also, *present* responses for the two-feature target conjunction of spatial frequency and orientation was equally fast and accurate, as compared with the single-feature targets of spatial frequency or orientation ($p > .05$).

Thus, significant conjunction benefits were observed for first-order features (Stimulus Set A only), consistent with previous research (Fournier et al., 2004). These results suggest that first-order features can prime decisions about a conjunction composed of first-order features.

Conjunction costs. For a given feature conjunction, there were two cases in which an *absent* response was made: when only one of the target features was present (i.e., one feature was consistent with a *present* response, whereas the other feature was consistent with an *absent* response; thus, decision competition) and when none of the target features were present (both features were consistent with an *absent* response; thus, no decision competition). Figure 3 shows that, when comparing the *absent* responses between these two cases, RT was longer and responding was less accurate in the first case involving decision competition than in the second case involving no decision competition.

A repeated measures ANOVA involving stimulus set (A or B) and target feature present (spatial frequency, orientation, or none) was computed on mean correct RT and mean

accuracy separately for the two-feature conjunction-absent judgments. The interaction between stimulus set and target feature was significant for RT [$F(2,30) = 63.48, p < .0001$] and for accuracy [$F(2,30) = 14.05, p < .0001$].

A Tukey's LSD test (with 1 and 15 degrees of freedom; $p < .05$) showed the following. For Stimulus Set A, *absent* response RT was longest when the target feature for which discrimination was fastest (i.e., orientation) was present, intermediate when the target feature for which discrimination was slowest (i.e., spatial frequency) was present, and shortest when none of the target features were present ($p < .05$). Also, *absent* responses were less accurate in Stimulus Set A when the target feature for which discrimination was fastest (i.e., orientation) was present ($p < .05$); accuracy did not differ between the conditions in which the target feature for which discrimination was slowest (i.e., spatial frequency) was present or none of the target features were present ($p > .05$). A similar pattern of results regarding *absent* response mean RT and accuracy was found for Stimulus Set B (all $ps < .05$).

Thus, incorrect priming that indicates the presence of a conjunction can lead to decision competition, which in turn interferes with the ability to make a fast and accurate *absent* judgment. Moreover, decision competition was greatest when the dimension for which discrimination was fastest incorrectly primed the presence of the conjunction, which is consistent with previous research (Fournier et al.,

Figure 3. Experiment 1: Mean correct *absent* response reaction times (RTs) and error rates for two-feature target judgments for the cases in which the target features of carrier spatial frequency (F) and carrier orientation (O) were present or neither target feature (None) was present. The left panel corresponds to Stimulus Set A, and the right panel corresponds to Stimulus Set B. Error bars represent one standard error of the mean.

1998; Fournier, Scheffers, et al., 2000). Thus, first-order features can prime decisions about a conjunction comprising two first-order features.

EXPERIMENT 2

We determined whether conjunction benefits and costs occur for the first-order dimension of carrier spatial frequency and the second-order dimension of envelope orientation and, thus, whether first- or second-order features can prime decisions made about a conjunction composed of first- and second-order features. In doing so, we investigated whether first- and second-order signals are combined after the discrimination of stimulus properties for each system.

Method

In each stimulus set, the Gabor stimuli differed across the first-order dimension of spatial frequency of the carrier and across the second-order dimension of envelope orientation. Carrier orientation was fixed at 45° (see Figure 4). In Stimulus Set A, the discrimination of spatial frequency was designed to be slower than the discrimination of orientation. Specifically, the spatial frequency of the carrier was either 7.7 or 9.7 cyc/deg, and the orientation of the envelope was either vertical or horizontal, with an aspect ratio of 2.42 or 0.412, respectively. In Stimulus Set B, the discrimination of orientation was designed to be slower than the discrimination of spatial frequency. Specifically, the spatial frequency of the carrier was either 6.7 or 10.7 cyc/deg, and the orientation of the envelope was either vertical or horizontal, with an aspect ratio of 1.16 or 0.824, respectively.⁵

There were four possible single-feature judgments: low spatial frequency, high spatial frequency, envelope oriented vertically, and envelope oriented horizontally. There were four possible two-feature judgments: low spatial frequency and envelope oriented vertically, low spatial frequency and envelope oriented horizontally, high spatial frequency and envelope oriented vertically, and high spatial frequency and envelope oriented horizontally. Throughout the experiment, each participant judged the presence or absence of one spatial frequency, one envelope orientation, and one spatial-frequency–envelope-orientation combination. This means that the variable of target feature judgment (levels: spatial frequency, orientation, and spatial-frequency–orientation combination) was run as a within-subjects factor.

Results

Conjunction benefits. Figure 5 shows correct RTs and percentages of errors for *present* and *absent* responses for each target feature across the two stimulus sets (A and B). The figure shows that conjunction benefits occurred for both Stimulus Sets A and B: *Present* responses were faster and more accurate for the two-feature target conjunction of spatial frequency and orientation than for the single-feature target for which discrimination was slowest (i.e., spatial frequency in Stimulus Set A and orientation in Stimulus Set B).

A repeated measures ANOVA involving response type (present or absent), stimulus set (A or B), and target feature (spatial frequency, orientation, or spatial-frequency–orientation) was computed for mean correct RT and mean

Figure 4. Stimulus sets used in Experiment 2, in which the Gabor stimuli varied across the first-order dimension of carrier spatial frequency and the second-order dimension of envelope orientation. The left panel shows Gabor stimuli from Stimulus Set A, and the right panel shows Gabor stimuli from Stimulus Set B.

accuracy separately. With respect to correct RT, there was a significant main effect of response type [$F(1,15) = 11.77, p < .01$] and a significant two-way interaction between stimulus set and target feature [$F(2,30) = 46.77, p < .0001$]. With regard to accuracy, there were significant two-way interactions between stimulus set and response type [$F(1,15) = 8.39, p < .05$], stimulus set and target feature [$F(2,30) = 15.17, p < .0001$], and response type and target feature [$F(2,30) = 12.86, p < .0001$].

The Tukey LSD test (1 and 15 degrees of freedom; $p < .05$) was used to evaluate whether mean RT and mean accuracy differed between the single-feature targets and whether conjunction benefits were observed for the two-feature targets in each stimulus set. For Stimulus Set A, both *present* and *absent* response RTs were significantly longer for spatial frequency than for orientation ($p < .05$). Also, *present* and *absent* response accuracy was lower for spatial frequency than for orientation but was significant

Figure 5. Experiment 2: Mean correct reaction times (RTs) and percentages of errors for *present* and *absent* responses to the target features of carrier spatial frequency (F) and envelope orientation (O) and the conjunction of carrier spatial frequency and envelope orientation (F-O). The left panel corresponds to Stimulus Set A, and the right panel corresponds to Stimulus Set B. Error bars represent one standard error of the mean.

only for *absent* responses ($p < .05$), not *present* responses ($p = .28$). Moreover, *present* responses were significantly faster and more accurate for the two-feature target of spatial frequency and orientation than for the single-feature target of spatial frequency ($p < .05$). For Stimulus Set B, both *present* and *absent* responses were slower and less accurate for orientation than for spatial frequency ($p < .05$). Moreover, *present* responses were significantly faster and more accurate for the two-feature target of spatial frequency and orientation than for the single-feature target of orientation ($p < .05$).

Thus, conjunction benefits were found for first-order and second-order features, based on spatial frequency of the carrier and orientation of the envelope, respectively. These results suggest that first-order features and second-order features can prime decisions about a conjunction involving both types of features.

Conjunction costs. Figure 6 shows that *absent* responses were slower and less accurate when one target feature was present and the other was absent (decision competition) than when none of the target features were present (no competition). Thus, as in Experiment 1, decision competition interfered with the ability to make a fast and accurate response regarding the absence of a given conjunction.

A repeated measures ANOVA involving stimulus set (A or B) and target feature present (spatial frequency, orientation, or none) was computed for mean correct *absent*

response RT and mean *absent* response accuracy separately for the two-feature judgments. There was a significant interaction between stimulus set and target feature for *absent* response RT [$F(2,30) = 11.81, p < .001$], as well as for *absent* response accuracy [$F(2,30) = 27.21, p < .0001$].

A Tukey's LSD test (1 and 15 degrees of freedom; $p < .05$) showed the following. For Stimulus Set A, *absent* response RT was longest when the target feature for which discrimination was fastest (i.e., orientation) was present, intermediate when the target feature for which discrimination was slowest (i.e., spatial frequency) was present, and shortest when none of the target features were present ($p < .05$). Also, *absent* responses were less accurate in Stimulus Set A when the target feature for which discrimination was fastest (i.e., orientation) was present ($p < .05$). Accuracy did not differ between the conditions in which the target feature that was discriminated most slowly (i.e., spatial frequency) was present or none of the target features were present ($p > .05$). For Stimulus Set B, *absent* responses were slowest and least accurate when the target feature for which discrimination was fastest (i.e., spatial frequency) was present, intermediate in speed and accuracy when the target feature for which discrimination was slowest (i.e., orientation) was present, and fastest and most accurate when none of the target features were present ($p < .05$).

Figure 6. Experiment 2: Mean correct *absent* response reaction times (RTs) and error rates for two-feature target judgments for the cases in which the target features of carrier spatial frequency (F) or envelope orientation (O) were present or neither target feature (None) was present. The left panel corresponds to Stimulus Set A, and the right panel corresponds to Stimulus Set B. Error bars represent one standard error of the mean.

Thus, decision competition hindered *absent* judgments when either a first-order target feature (spatial frequency of the carrier) or a second-order target feature (orientation of the envelope) was present. Moreover, decision competition was greatest when the feature for which discrimination was the fastest, either first order or second order, incorrectly primed the presence of a conjunction.

GENERAL DISCUSSION

This study has shown that conjunction benefits and costs occur for target conjunctions composed of first-order features and for target conjunctions composed of first-order and second-order features. Thus, first-order features can prime decisions about a conjunction composed of first-order features, and first-order or second-order features can prime decisions about a conjunction composed of both types of features. Second-order features were shown to prime decisions even though the visual processing of second-order and first-order stimuli may be fundamentally different (Calvert et al., 2005; Harris & Smith, 1992; Lu & Sperling, 1996; Manahilov et al., 2005; Nishida et al., 1994; Schofield & Georgeson, 1999; Smith & Ledgeway, 1997; Smith & Scott-Samuel, 2001; but see Benton et al., 1997, and Johnston et al., 1992, for an opposing view). Furthermore, because conjunction benefits and costs were found for stimuli composed of both first- and second-order features, this indicates that the two types of signals can be combined at a decision stage of processing after the discrimination of stimulus properties occurs for each system. This finding is inconsistent with the idea that outputs from these independent mechanisms are combined (e.g., into an object file) and then submitted to a unitary decision process involving discrimination of the composite stimulus (Farell, 1984; Ratcliff, 1978), an implicit and, sometimes, explicit assumption in many feature integration and object-based selection models (e.g., Cave, 1999; Duncan, 1984; Duncan & Nimmo-Smith, 1996; Treisman & Gelade, 1980; Treisman & Sato, 1990; Wolfe, 1994).⁶

The stimuli composed of first-order features (the spatial frequency and orientation of the carrier in Experiment 1) and the stimuli composed of first- and second-order features (the spatial frequency of the carrier and envelope orientation in Experiment 2) could be considered integral dimensions because each pair of attributes was derived from the definition of a Gabor stimulus. According to Garner (1974), integral dimensions involve co-existence, and these dimensions are selected together, whereas separable dimensions entail independent existence and these dimensions are not necessarily selected together. Although the two dimensions (first order or first order and second order) may be selected together, there is evidence that the time taken to make a *decision* regarding the presence of a single-feature target was determined only by the feature on the task-relevant dimension, and not also by the feature on the task-irrelevant dimension. If the feature on the task-irrelevant dimension had contributed to the decision, the single-feature discriminations should be delayed relative to the conjunction discriminations because, in the former case, the discrimination process must generalize across

a set of possible stimuli that have different values on the unspecified dimension. In contrast to this prediction, equivalent *present* response RTs are consistently found between conjunction and single-feature targets defined as integral stimuli when the discrimination speed between the single-feature targets is similar (see the data obtained in Experiment 1, Stimulus Set B in Figure 2; see also the discussion in Fournier et al., 2004). Also, *present* response RTs for conjunction discriminations are not shorter, relative to the single feature for which discrimination is fastest (see the present data, as well as Fournier, Bowd, & Herbert, 2000; Fournier et al., 1998; Fournier et al., 2004; Fournier, Scheffers, et al., 2000).

Conjunction benefits occurred only if the target features that made up the conjunction significantly differed in their speed of discriminability, which has been reported previously (see Fournier, Bowd, & Herbert, 2000; Fournier et al., 1998; Fournier et al., 2004; Fournier, Scheffers, et al., 2000). Responses indicating the presence of a conjunction were faster (and more accurate) than those indicating the presence of the single feature for which discrimination was slowest. Thus, the feature for which discrimination was fastest primed the presence of a conjunction before the feature for which discrimination was slowest affected responding, and this occurred regardless of whether the features were first order or second order. These findings demonstrate that differences in discrimination time between a first-order feature and a second-order feature can influence perceptual identification of a stimulus composed of these two types of features.

Conjunction costs occurred when observers indicated the absence of a conjunction and one of the two target features that made up the conjunction was present in the stimulus; this has also been reported previously (Fournier et al., 1998; Fournier, Scheffers, et al., 2000). Moreover, the size of the conjunction cost—in terms of delayed responding or error rate—was greater when the feature for which discrimination was fastest, as opposed to the feature for which discrimination was slowest, was present. Thus, the feature for which discrimination was fastest primed a response indicating the presence of a conjunction before the feature for which discrimination was slowest could indicate the absence of a conjunction, and this also occurred regardless of whether the features were first order or second order.

These findings are consistent with an asynchronous priming model (Fournier et al., 2004), which assumes that a feature for which discrimination is fastest—either first order or second order—can partially activate and, therefore, prime a decision about the occurrence of a feature conjunction. According to this model, each feature on a task-relevant dimension can independently activate its task-relevant decision (e.g., present or absent) in a parallel, continuous fashion. Also, features that are discriminated more quickly can partially activate decisions earlier than can features that are discriminated more slowly. Accumulating decision activation elicited by each of the two features is then temporally combined at a central decision stage in working memory to meet a single decision criterion as to whether the conjunction is present or absent

(e.g., Cohen & Shoup, 1997; Fournier et al., 2004; see also Bundesen, 2002; Duncan, 1996; Heathcote, Walker, & Hitch, 1994; Isenberg, Nissen, & Marchak, 1990; Stefurak & Boynton, 1986). When features on the task-relevant dimensions are mapped to the same response (e.g., present), conjunction benefits result from early decision activation by features on the more discriminable dimensions, which are combined with activation by features on the less discriminable dimensions. That is, early decision priming allows the decision threshold representing the presence of the conjunction to be reached earlier than the decision threshold representing the presence of the feature for which discrimination is slowest. However, if one feature indicates that the conjunction is present and the other feature indicates that the conjunction is absent, a conjunction cost will occur, because the accumulation of information indicating that the conjunction is absent must countermand the incorrect information that the conjunction is present in order for the correct decision to be made. This, in turn, will lead to a delay in determining that the conjunction is absent, as compared with the case in which both features indicate that the conjunction is absent. Furthermore, conjunction costs will be greater if the feature that is present is discriminated more quickly than the feature that is absent. In this case, the feature that is present will prime the presence of the conjunction earlier and, hence, will require more time for the feature that is discriminated more slowly to generate sufficient countermanding activation to override this initial, incorrect priming and lead to a correct decision that the conjunction is absent.

The existence of conjunction costs suggests that the accumulation of information about first-order and second-order features is independently processed to the extent that each can potentially prime a decision as to whether a conjunction target is present or absent *before* the composite representation of the features on the task-relevant dimensions are analyzed. That is, the outputs from first-order and second-order processing were not combined (e.g., into an object file; Kahneman & Treisman, 1984; Kahneman, Treisman, & Gibbs, 1992) and then submitted to a unitary decision process involving discrimination of the composite stimulus. If this had been the case, the time taken to render a decision about the absence of the target feature conjunction should have been the same when only one of the target features was presented as when neither was presented. However, in our study, when a target conjunction was absent, RT was longer and accuracy less when one of the target features was presented than when neither was presented. This suggests that first-order and second-order signals were identified to the extent that each could partially activate (prime) a decision as to whether a conjunction target was present or absent *before* the composite representation of these signals was discriminated.

Our results are relevant to those in Smith and Scott-Samuel (2001), who showed that discrimination of the spatial frequency or speed of movement at suprathreshold levels was facilitated when first-order and second-order stimuli were combined, provided that overall contrast was low. Recall that these authors suggested that first-order

and second-order signals are initially detected by independent mechanisms and then the outputs either are combined at a decision stage of processing only after discrimination of stimulus properties occurs within each system or are combined at a decision stage prior to the operation of a single process involving discrimination of the composite stimulus. The results of the present study show that the two types of signals can be combined at a decision stage of processing after the discrimination of stimulus properties occurs for each system.

AUTHOR NOTE

Correspondence concerning this article should be addressed to L. R. Fournier, Department of Psychology, Washington State University, Pullman, WA 99164-4820 (e-mail: fournier@wsunix.wsu.edu).

REFERENCES

- BENTON, C. P., JOHNSTON, A., & MCOWAN, P. W. (1997). Perception of motion direction in luminance- and contrast-defined reversed-phi motion sequences. *Vision Research*, *37*, 2381-2399.
- BUNDESEN, C. (2002). A general theory of visual attention. In L. Bäckman & C. von Hofsten (Eds.), *Psychology at the turn of the millennium: Vol. 1. Cognitive, biological, and health perspectives* (pp. 179-200). Hove, U.K.: Psychology Press.
- CALVERT, J., MANAHILOV, V., SIMPSON, W. A., & PARKER, D. M. (2005). Human cortical responses to contrast modulations of visual noise. *Vision Research*, *45*, 2218-2230.
- CAVE, K. R. (1999). The FeatureGate model of visual selection. *Psychological Research*, *62*, 182-194.
- COHEN, A., & SHOUP, R. (1997). Perceptual dimensional constraints in response selection processes. *Cognitive Psychology*, *32*, 128-181.
- COHEN, A., & SHOUP, R. (2000). Response selection processes for conjunctive targets. *Journal of Experimental Psychology: Human Perception & Performance*, *26*, 391-411.
- DAUGMAN, J. G. (1985). Uncertainty relation for resolution in space, spatial frequency, and orientation optimized by two-dimensional visual cortical filters. *Journal of the Optical Society of America*, *2*, 1160-1169.
- DUNCAN, J. (1980). The demonstration of capacity limitation. *Cognitive Psychology*, *12*, 75-96.
- DUNCAN, J. (1984). Selective attention and the organization of visual information. *Journal of Experimental Psychology: General*, *114*, 501-517.
- DUNCAN, J. (1996). Cooperating brain systems in selective perception and action. In T. Inui & J. L. McClelland (Eds.), *Attention and performance XVI: Information integration in perception and communication* (pp. 549-578). Cambridge, MA: MIT Press, Bradford Books.
- DUNCAN, J., & NIMMO-SMITH, I. (1996). Objects and attributes in divided attention: Surface and boundary systems. *Perception & Psychophysics*, *58*, 1076-1084.
- ERIKSEN, C. W., & SCHULTZ, D. W. (1979). Information processing in visual search: A continuous flow conception and experimental results. *Perception & Psychophysics*, *25*, 249-263.
- FARELL, B. (1984). Attention in the processing of complex visual displays: Detecting features and their combinations. *Journal of Experimental Psychology: Human Perception & Performance*, *10*, 40-64.
- FLOWERS, J. H., & WILCOX, N. (1982). The effect of flanking context on visual classification: The joint contribution of interactions at different processing levels. *Perception & Psychophysics*, *32*, 581-591.
- FOURNIER, L. R., BOWD, C., & HERBERT, R. J. (2000). Interference from multi-dimensional objects during feature and conjunction discriminations. *Quarterly Journal of Experimental Psychology*, *53A*, 191-209.
- FOURNIER, L. R., & ERIKSEN, C. W., & BOWD, C. (1998). Multiple-feature discrimination faster than single-feature discrimination within the same object? *Perception & Psychophysics*, *60*, 1384-1405.
- FOURNIER, L. R., HERBERT, R. J., & FARRIS, C. (2004). Demands on attention and the role of response priming in visual discrimination of feature conjunctions. *Journal of Experimental Psychology: Human Perception & Performance*, *30*, 836-852.

- FOURNIER, L. R., SCHEFFERS, M. K., COLES, M. G. H., ADAMSON, A., & ABAD, E. V. (2000). When complexity helps: An electrophysiological analysis of multiple feature benefits in object perception. *Acta Psychologica*, **104**, 119-142.
- GARNER, W. R. (1974). *The processing of information and structure*. Potomac, MD: Erlbaum.
- GRICE, G. R., BOROUGHS, J. M., & CANHAM, L. (1984). Temporal dynamics of associative interference and facilitation produced by visual context. *Perception & Psychophysics*, **36**, 499-507.
- HARRIS, L. R., & SMITH, A. T. (1992). Motion defined exclusively by second-order characteristics does not evoke optokinetic nystagmus. *Visual Neuroscience*, **9**, 565-570.
- HAWKINS, H. L. (1969). Parallel processing in complex visual discrimination. *Perception & Psychophysics*, **5**, 56-64.
- HEATHCOTE, D., WALKER, P., & HITCH, G. J. (1994). Feature independence and the recovery of feature conjunctions. *Journal of General Psychology*, **121**, 253-266.
- HOCHSTEIN, S., & AHISSAR, M. (2002). View from the top: Hierarchies and reverse hierarchies in the visual system. *Neuron*, **36**, 791-804.
- HOLLIDAY, I. E., & ANDERSON, S. J. (1994). Different processes underlie the detection of second order motion at low and high temporal frequencies. *Proceedings of the Royal Society of London: Series B*, **257**, 165-173.
- ISENBERG, L., NISSEN, M. J., & MARCHAK, L. C. (1990). Attentional processing and the independence of color and orientation. *Journal of Experimental Psychology: Human Perception & Performance*, **16**, 869-878.
- JAMES, T. W., HUMPHREY, K. G., GATI, J. S., MENON, R. S., & GOODALE, M. A. (2000). The effects of visual object priming on brain activation before and after recognition. *Current Biology*, **10**, 1017-1024.
- JOHNSTON, A., MCOWAN, P. W., BUXTON, H. (1992). A computational model of the analysis of some 1st-order and 2nd-order motion patterns by simple and complex cells. *Proceedings of the Royal Society of London: Series B*, **250**, 297-306.
- KAHNEMAN, D., & TREISMAN, A. (1984). Changing views of attention and automaticity. In R. Parasuraman & D. R. Davies (Eds.), *Varieties of attention* (pp. 29-61). New York: Academic Press.
- KAHNEMAN, D., TREISMAN, A., & GIBBS, B. (1992). The reviewing of object files: Object-specific integration of information. *Cognitive Psychology*, **24**, 175-219.
- LAVIE, N. (1995). Perceptual load as a necessary condition for selective attention. *Journal of Experimental Psychology: Human Perception & Performance*, **21**, 451-468.
- LU, Z.-L., & SPERLING, G. (1996). Contrast gain control in first- and second-order motion perception. *Journal of the Optical Society of America A*, **13**, 2305-2318.
- MANAHILOV, V., SIMPSON, W. J., & CALVERT, J. (2005). Why is second-order vision less efficient than first-order vision? *Vision Research*, **5**, 2759-2772.
- MARCELJA, S. (1980). Mathematical description of the responses of simple cortical cells. *Journal of the Optical Society of America*, **70**, 1297-1300.
- NICKERSON, R. S. (1972). Binary-classification reaction time: A review of some studies of human information-processing capabilities. *Psychonomic Monograph Supplements*, **4** (17, Whole No. 65), 275-317.
- NICKERSON, R. S. (1973). Frequency, recency, and repetition effects on same and different response times. *Journal of Experimental Psychology*, **101**, 330-336.
- NISHIDA, S., ASHIDA, H., & SATO, T. (1994). Complete interocular transfer of motion aftereffect with flickering test. *Vision Research*, **34**, 2707-2716.
- RATCLIFF, R. (1978). A theory of memory retrieval. *Psychological Review*, **85**, 59-108.
- SCHOFIELD, A. J., & GEORGESON, M. A. (1999). Sensitivity to modulations of luminance and contrast in visual white noise: Separate mechanisms with similar behaviour. *Vision Research*, **39**, 2697-2716.
- SCHOFIELD, A. J., GEORGESON, M. A. (2003). Sensitivity to contrast modulation: The spatial frequency dependence of second-order vision. *Vision Research*, **43**, 243-259.
- SCOTT-SAMUEL, N. E., & GEORGESON, M. A. (1999). Does early non-linearity account for second-order motion? *Vision Research*, **39**, 2853-2865.
- SMITH, A. T., & LEDGEWAY, T. (1997). Separate detection of moving luminance and contrast modulations: Fact or artifact? *Vision Research*, **37**, 45-62.
- SMITH, A. T., & SCOTT-SAMUEL, N. E. (2001). First-order and second-order signals combine to improve perceptual accuracy. *Journal of the Optical Society of America A*, **18**, 2267-2272.
- STEFURAK, D. L., & BOYNTON, R. M. (1986). Independence of memory for categorically different colors and shapes. *Perception & Psychophysics*, **39**, 164-174.
- TANAKA, Y., & SAGI, D. (2000). Attention and short-term memory in contrast detection. *Vision Research*, **40**, 1089-1100.
- TREISMAN, A. M., & GELADE, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, **12**, 97-136.
- TREISMAN, A. M., & SATO, S. (1990). Conjunction search revisited. *Journal of Experimental Psychology: Human Perception & Performance*, **16**, 459-478.
- WILSON, H. R., FERRERA, V. P., & YO, C. (1992). A psychophysically motivated model for two-dimensional motion perception. *Visual Neuroscience*, **9**, 79-97.
- WOLFE, J. M. (1994). Visual search in continuous, naturalistic stimuli. *Vision Research*, **34**, 1187-1195.
- WOODS, D. L., ALAIN, C., & OGAWA, K. H. (1998). Conjoining auditory and visual features during high-rate serial presentation: Processing and conjoining two features can be faster than processing one. *Perception & Psychophysics*, **60**, 239-249.

NOTES

1. One reviewer suggested that an explanation of conjunction benefits may require the existence of feedback connections from the central decision process to individual features analyzers that alter the decision threshold of each analyzer. This approach would account for conjunction benefits by assuming that once the decision process is primed by the feature that is discriminated more quickly, feedback connections lower the threshold of the other analyzer so that the target conjunction is discriminated more quickly than the slowest feature judged in isolation. However, this account would also predict that conjunction benefits are due to fast guesses. In contrast to this prediction, past research has shown that for *present* responses, error RTs are overall longer than correct RTs for each feature judgment and that the error RT pattern across feature judgments is similar to that found for correct RTs (e.g., Fournier et al., 1998). Also, past research has shown that when a flanker is incompatible with the target on the dimension that is discriminated most slowly (shape), RT is equally inflated for the conjunction target (hue and shape) and the single-feature target (shape) for which discrimination is slowest (e.g., Fournier et al., 2004). Moreover, this approach has difficulty accounting for conjunction costs when the more quickly discriminated feature is mapped to the present response. Lowering the threshold for the other analyzer would not benefit the decision process because a nontarget feature would be presented, and a speed-accuracy trade-off would be predicted for stimulus situations in which one target feature was present and the other was absent. However, a speed-accuracy trade-off has never been observed.

2. Note that the priming that occurs in the conjunction benefits and costs paradigm is related to the information content of a given feature. Evidence for this comes from Fournier et al. (2004), who showed that conjunction benefits do not occur when the target is defined by a disjunctive conjunction (i.e., where the observer is required to determine the presence or absence of two different feature conjunctions, such as a red X or a green O), because the information content from a single feature is insufficient to prime the presence of a particular conjunction. In this example, the presence of a feature for which discrimination is fastest—say, the red hue—does not prime the response to a conjunction, because either hue, red or green, is consistent with one of the target conjunctions.

3. We used Gabor stimuli to address the functional relationship between first-order and second-order processing. These stimuli match the sensitivity profile of receptive fields of cortical simple cells well. By using these stimuli, we are not implying that only primary visual cortical areas are involved in the processing of such stimuli. As was proposed by Hochstein and Ahissar (2002), using vision to consciously scrutinize a target conjunction may involve higher level visual areas that focus attention via feedback connections onto low-level mechanisms.

4. Because *present* responses were less frequent than *absent* responses for the two-feature judgments, responding may have been more con-

servative for the two-feature *present* responses. However, past research has shown that conjunction benefits still occur even with this possible response bias (e.g., Fournier et al., 2004).

5. Asymmetry in the aspect ratios was due to the fact that pixels were not perfectly square. Due to its irrelevance to our hypotheses, the effect of this asymmetry on response time was not explicitly tested. Rather, responses were averaged across vertically and horizontally oriented envelopes, and any variability in response time due to asymmetry in aspect ratio ended up in the error terms of the ANOVAs. Hence, the effect of these asymmetries was limited to a potential reduction in the power of the analyses used.

6. The goal of these theories is to describe visual search and, hence, what happens before attention selects information that is used to create

an object representation. Thus, our findings do not challenge the core assumptions of these theories, which concern the visual search process. Our findings question only the theories' assumptions that features are integrated by attention before a decision can be activated and that it is the integrated object (as opposed to the individual task-relevant features of the attended object) that is then submitted to a unitary decision process involving discrimination of the composite stimulus.

(Manuscript received February 15, 2006;
revision accepted for publication May 25, 2007.)