

# The Structure of Attentional Control: Contingent Attentional Capture by Apparent Motion, Abrupt Onset, and Color

Charles L. Folk, Roger W. Remington, and Joseph H. Wright

Five spatial cuing experiments tested 2 hypotheses regarding attentional capture: (a) Attentional capture is contingent on endogenous attentional control settings, and (b) attentional control settings are limited to the distinction between dynamic and static discontinuities (C. L. Folk, R. W. Remington, & J. C. Johnston, 1992). In Experiments 1 and 2, apparent-motion precues produced significant costs in performance for targets signaled by motion but not for targets signaled by color or abrupt onset. Experiment 3 established that this pattern is not due to differences in the difficulty of target discrimination. Experiments 4 and 5 revealed asymmetric capture effects between abrupt onset and apparent motion related to stimulus salience. The results support the hypotheses of Folk et al. (1992) and suggest that stimulus salience may also play a role in attentional capture.

An organism that interacts with its environment is faced with many stimulus events, each of which may hold some relevance for action. Limitations on information processing, however, necessitate a selection mechanism responsible for choosing from this menu of events those that will influence behavioral responses at any given point in time (Bundesen, 1990; Cave & Wolfe, 1990; Hoffman, 1979; Neisser, 1967; Yantis & Jonides, 1990). Theories of this selection process in the visual domain come under the heading of visual selective attention. In the context of these theories, visual events that are selected are those to which attentional resources are allocated.

Current models of visual selective attention emphasize the development of an "allocation schedule" in which candidate stimulus events are prioritized for access to attentional resources (Bundesen, 1990; Cave & Wolfe, 1990; Duncan & Humphreys, 1989; Koch & Ullman, 1985; Treisman & Sato, 1990; Ullman, 1984; Yantis & Jonides, 1990). In most of these models, prioritization is a combined function of both "bottom-up" or stimulus factors and "top-down" or goal-directed factors. A substantial literature suggests, however, that certain stimulus events, such as abrupt visual onsets, enjoy an inherently high priority in the allocation schedule,

resulting in the purely stimulus-driven "capture" of attentional resources (Jonides, 1980; Jonides & Yantis, 1988; Müller & Rabbit, 1989; Posner, 1980; Remington, Johnston, & Yantis, 1992; Theeuwes, 1991b, 1992; Yantis & Johnson, 1990; Yantis & Jones, 1991; Yantis & Jonides, 1984).

Folk, Remington, and Johnston (1992) have recently challenged the contention that attentional capture by abrupt onset is purely stimulus-driven or "bottom-up." According to their contingent involuntary orienting hypothesis, involuntary shifts of attention, even those elicited by abrupt onsets, are ultimately contingent on endogenous "attentional control settings." These control settings reflect high-level, task-induced behavioral goals. Folk et al. (1992) found that an irrelevant spatial precue defined by a color discontinuity or an abrupt onset produced attentional capture only when the target was defined by the same or similar property. The present experiments tested the generality of this form of attentional control. Our goals were to determine whether the results of Folk et al. (1992) generalize to stimulus properties other than color and abrupt onset and, if so, to investigate the functional stimulus classes for which attentional control settings can be instantiated.

## Top-Down Modulation of Attentional Capture

Investigations of stimulus-driven shifts of spatial attention (i.e., attentional capture) fall into two general classes: (a) spatial-cuing studies in which performance is measured as a function of the validity of advance information about the spatial location of a target, and (b) visual-search studies in which performance is measured as a function of display size (i.e., the number of elements in the display). Both paradigms have yielded evidence that abrupt luminance increments produce involuntary shifts of spatial attention. In spatial-cuing experiments, peripheral, abrupt-onset or luminance-increment cues produce shifts in the spatial distribution of attention that are characteristic of an automatic process; the shifts are insensitive to probabilistic foreknowledge of cue validity (Jonides, 1981; Müller & Findlay, 1987; Müller &

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Rabbitt, 1989; Posner & Cohen, 1984; Remington, Johnston, & Yantis, 1992) and are unaffected by concurrent processing load or task expectancies (Jonides, 1981). In visual-search studies the effect of display size can be eliminated when targets are presented as abrupt onsets among gradually onset distractors, suggesting that attention is captured by the abruptly onset target (Yantis & Johnson, 1990; Yantis & Jonides, 1984, 1990). Similar effects have been demonstrated for abrupt offsets (Miller, 1989; Theeuwes, 1991b). It has been argued that the involuntary allocation of resources to abrupt luminance changes may represent a unique and "hard-wired" adaptive response, which serves to orient the organism to unexpected and ecologically important stimulus events (Jonides & Yantis, 1988; Yantis & Jonides, 1984).

Recent evidence, however, indicates that attentional capture by abrupt luminance changes do not occur under all circumstances (Folk et al., 1992; Theeuwes, 1991a; Yantis & Jonides, 1990), challenging the claim that such capture represents a "hard-wired" response. For example, Yantis and Jonides (1990), as well as Theeuwes (1991a), reported that abrupt luminance changes do not produce capture when attention is focused on a particular location prior to the luminance change. This suggests that attentional capture occurs only under conditions of spatial uncertainty, when subjects' attention is in a spatially distributed or unfocused state.

Folk et al. (1992) have recently proposed a new perspective on the conditions under which abrupt onsets will involuntarily capture attention and, more generally, on the mechanisms underlying attentional capture. They argue that attentional capture is not purely a function of the presence of a stimulus property (e.g., onset) but depends on the existence of a prior attentional "set" for the eliciting property. This proposal was based on the results of a spatial-cuing task in which peripheral, abruptly onset spatial precues appeared 150 ms prior to a target character that could appear in one of four peripheral locations. The validity of the cue as an indicator of the exact target location was varied across blocks of trials (Experiments 1, 2, and 4) such that in the critical condition, the cue was 100% invalid. Elevated response times for 100% invalid cues relative to control conditions were assumed to reflect attentional capture by the abrupt-onset cue.

Attentional set for specific stimulus properties was manipulated by varying the property required to locate the target. In one condition, the target was a single, abruptly onset character. In another, characters appeared in all four locations and subjects were required to identify the character that differed in color from the rest (i.e., the color singleton). Invalid, abrupt-onset precues interfered with the identification of onset targets but not color targets. Likewise, follow-up experiments showed that invalid color precues interfered with the identification of color targets but not abrupt-onset targets.<sup>1</sup>

Folk et al. (1992) concluded that abrupt onsets, as well as other stimulus properties, can produce involuntary shifts of attention (i.e., attention capture), but that such shifts are contingent on the establishment of an attentional control setting for the eliciting property. The authors referred to this proposal as the contingent involuntary orienting hypothesis. According to the hypothesis, high-level cognitive processes de-

termine how the attentional control system is set; given a setting, however, the on-line response to events (e.g., attentional capture) is purely stimulus driven, remaining imperious to any further voluntary control (but see Yantis, 1993, for an alternative interpretation).

### The Functional Architecture of Attentional Control

In the context of the contingent involuntary orienting hypothesis, an important issue concerns the functional stimulus dimensions that constitute the set of potential control settings. Folk et al. (1992, Experiment 4) found that when cues and targets were both defined by discontinuities in color but differed with respect to the specific color value (e.g., a red cue paired with a green target), there were still significant costs associated with 100% invalid cues. Apparently, control settings cannot be established at the level of specific feature values along a given dimension (e.g., red or green). In related paradigms, Pashler (1988, Experiment 6) and Theeuwes (1991a, 1992) found that irrelevant color singletons interfered with search for form singletons and vice versa, suggesting that subjects are also unable to establish control settings at the level of feature dimensions (e.g., color or form).

These data, along with the selectivity in attentional capture observed between color and onset, led Folk et al. (1992) to hypothesize that attentional control settings are broadly tuned, distinguishing between only two functional stimulus classes: (a) dynamic discontinuities, defined by changes in stimulus properties over time (e.g., onset, offset, motion, and so on), and (b) static discontinuities, defined by discontinuities in stimulus properties across space (e.g., an "odd man out" in color, luminance, shape, orientation, binocular disparity, and so on). Accordingly, selectivity in attentional capture should be observed across (but not within) these two broad stimulus classes.

The static versus dynamic control architecture proposed by Folk et al. (1992) is based on the selectivity observed between only two stimulus types: abrupt onset and color discontinuity. Converging evidence for the proposed architecture is required before a claim of wider generality can be made. For example, the static-dynamic distinction suggests that selectivity in attention capture should be evident when color discontinuities are paired with dynamic discontinuities other than abrupt onset, such as motion. On the other hand, no selectivity should be observed between dynamic stimuli defined along different dimensions (e.g., abrupt luminance change vs. motion), or along different values within such dimensions (e.g., onset vs. offset or rotational vs. translational motion); these stimuli should be treated as functionally

<sup>1</sup> There is some controversy over whether these distraction effects can be considered a form of attentional capture (Folk, Remington, & Johnston, 1993; Yantis, 1993). Yantis argued that because subjects were set to respond to singleton targets, shifts of attention to singleton distractors should not be considered "involuntary" or stimulus driven. We argue that because such shifts violated the clear intentions of the observer to ignore distractors, they were indeed involuntary and stimulus driven (see Folk et al., 1993).

equivalent by the attention allocation system, just as analogous distinctions for static discontinuities appear to be (Pashler, 1988; Theeuwes, 1991a, 1992).

It is also important to rule out an alternate interpretation of the Folk et al. (1992) results. The stimuli used differed not only with respect to whether they were defined by dynamic or static discontinuities, but by whether they constituted a single item, as in the case of abruptly onset cues and targets, or a "field property," as in the case of color cues and targets. Thus, it is possible that this item versus field distinction defines the functional control architecture, rather than the hypothesized dynamic-static distinction.

### Focus of the Present Research

In the present studies, we address these issues by examining patterns of interference between abrupt onsets, color discontinuities, and apparent motion using the cuing paradigm adopted by Folk et al. (1992). Apparent motion is a type of dynamic discontinuity that can take different specific forms (e.g., translational or rotational motion). Thus, observing the pattern of selectivity in attentional capture when motion cues are paired with targets exhibiting different or similar forms of motion, as well as with targets signaled by an abrupt-onset or color discontinuity, provides a means of testing the proposed static versus dynamic architecture of attentional control. If the proposed architecture is correct, no selectivity in attention capture should obtain between specific forms of apparent motion (e.g., translational vs. rotational motion), nor between apparent motion and abrupt onset, since all of these stimulus properties represent forms of dynamic discontinuity. On the other hand, selectivity in attentional capture should be observed when motion or abrupt onset is paired with a static discontinuity in color.

The motion conditions also provide an important test of the generalizability of the contingent involuntary orienting hypothesis. As much as any other stimulus property, motion carries important ecological information such as the presence, location, and action of life-threatening and life-supporting stimuli (i.e., predators and prey). Moreover, there is substantial evidence for the existence of specialized neural systems directly responsible for the extraction of motion information (see Nakayama, 1985). Demonstrating that involuntary attentional shifts elicited by such a salient, ecologically important stimulus property are contingent on attentional control settings would provide important additional support for the notion of contingent involuntary orienting.

### Experiment 1

The design of the first experiment was adapted from Folk et al. (1992, Experiments 1 and 2). The validity of spatial precues was varied across blocks of trials. Attentional capture was indexed by costs in response time for the 100% invalid-cue condition relative to a neutral, noninformative-cue condition. Rotational-motion cues were paired in four separate, between-subject conditions with rotational-motion

targets, translational-motion targets, abrupt-onset targets, and color-discontinuity targets. Subjects made forced-choice responses with regard to the identity of the target ( $X$  vs.  $=$ ).

The contingent involuntary orienting hypothesis predicts that a rotational-motion cue should elicit involuntary attention shifts when paired with a rotational-motion target but not when paired with a color-discontinuity target. If, as proposed by Folk et al. (1992), attentional control settings are limited to the general classes of static versus dynamic discontinuities (i.e., if all dynamic discontinuities are treated as functionally equivalent regardless of the dimensions or specific values on which they are defined), then a rotational-motion cue should also elicit involuntary attention shifts for translational-motion targets as well as abrupt-onset targets. If apparent motion elicits involuntary shifts of attention regardless of attentional control settings, then costs for 100% invalid motion cues should obtain in all four target-property conditions. Such a result would represent a serious challenge to the contingent involuntary orienting hypothesis.

### Method

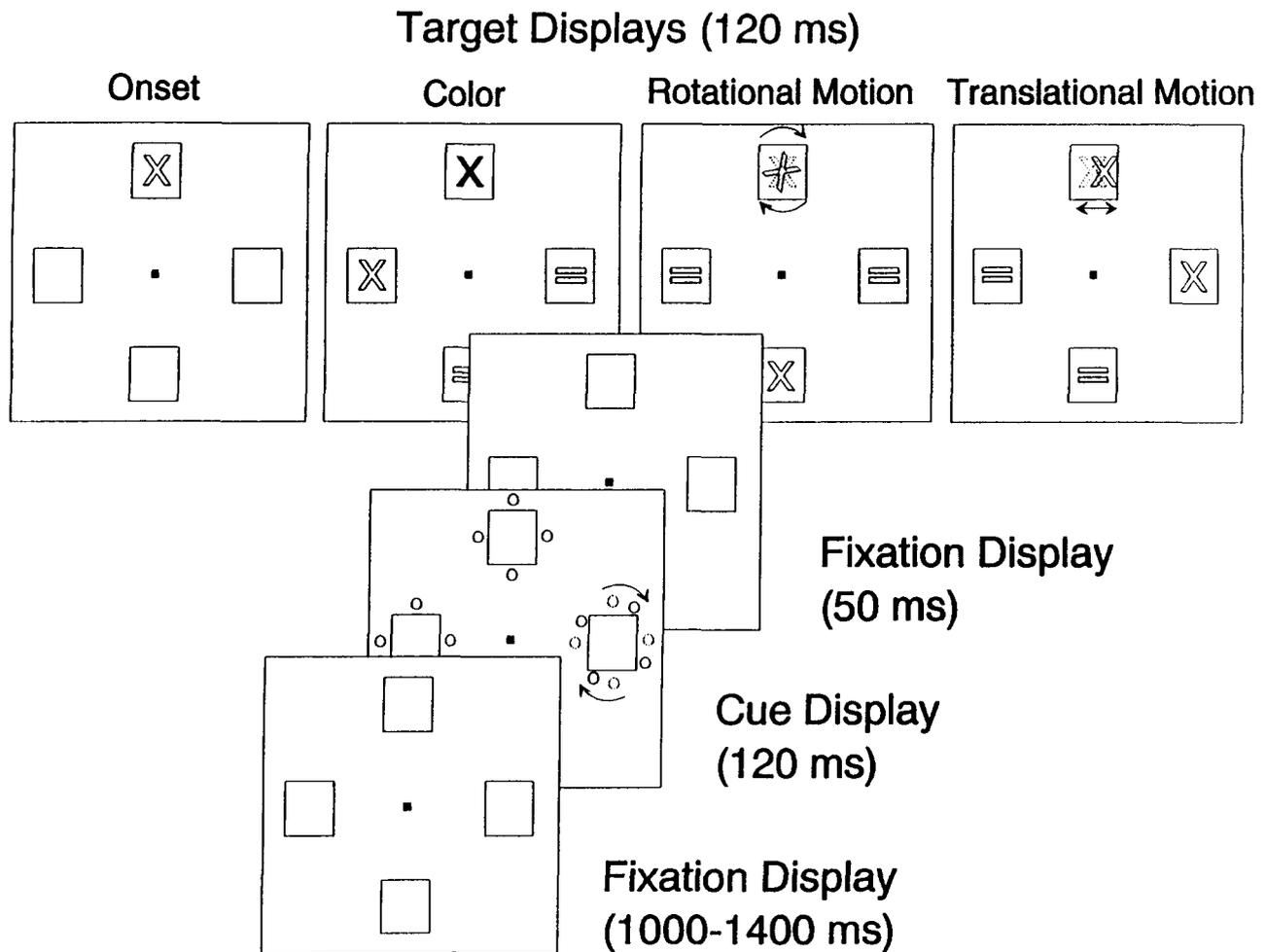
**Subjects.** Seventy-two subjects, aged 18 to 21, participated in this study in partial fulfillment of a class requirement. Subjects were recruited from the Villanova University Human Subjects Pool and were randomly assigned to one of four between-subjects experimental conditions. All subjects were tested for normal or corrected-to-normal near visual acuity (20/30 or better at a viewing distance of about 31 cm [14 in.] binocularly) and normal color vision using a Titmus II vision tester.

**Apparatus.** Stimulus displays were presented on a Princeton Graphics SR-12 monitor driven by a Zenith 286 microcomputer equipped with a Sigma Design, Color 400 high-resolution (680 × 400) graphics board. The monitor was placed at eye level on a wooden stand at a viewing distance of approximately 50 cm.

**Stimuli.** A fixation display, a cue display, and a target display were presented on each trial (see Figure 1). The fixation display consisted of a fixation cross (.34° × .34° visual angle) surrounded by four peripheral boxes (1.15° × 1.15°) placed 4.1° above, below, to the left, and to the right of the cross. All boxes were light gray (IBM color designation No. 8) against the black background of the cathode-ray tube (CRT) screen.

Cue displays involved the presentation of three successive 40-ms frames with zero interstimulus interval (ISI). Frame 1 consisted of the fixation display with the addition of sets of four small circles (.23° in diameter) placed in a diamond configuration around each box. The circles were high-contrast white (IBM color designation No. 15) against the black CRT screen and were centered .3° from the midpoint of the adjacent box side. In Frame 2, the circles around one of the four boxes were extinguished and a new set of circles appeared at a location .79 radians (linear displacement of 39.6' of visual angle) away on an imaginary circle of diameter .875°, centered on the box. Frame 3 was identical to Frame 1. The shifting circles were designated as the cue. All subjects reported apparent rotational motion for this set of circles.

Target displays consisted of the characters  $X$  (.5° × .5°) and  $=$  (.7° × .3°) appearing inside the boxes surrounding fixation. All characters (except as noted below) were high-contrast white (IBM color designation No. 15) against the black CRT screen. In the rotational-motion condition, the target was indicated by a rotational displacement of one of the characters over three successive 40-ms frames with zero ISI. In Frame 1, a character appeared in each box.



*Figure 1.* Representation of trial events and target-property conditions in Experiment 1. Displays are not necessarily to scale. See text for details regarding actual measurements and procedures for creating apparent motion.

In Frame 2, one of the characters was oriented  $45^\circ$  from its normal orientation. Frame 3 was identical to Frame 1. All subjects reported apparent rotational motion for the rotationally displaced character. In the translational-motion condition, the frames and sequencing were identical to the rotational-motion condition, except the target underwent a rightward lateral displacement of  $.32^\circ$  visual angle in Frame 2 rather than a rotational displacement. All subjects reported apparent translational (horizontal) motion for this character. In the onset-target condition, a single white character was presented in 1 of the boxes for 120 ms. In the color-target condition, three boxes contained white characters and one (the target) contained a high-contrast red character (IBM color designation No. 12). Color-target displays were presented for 120 ms.

*Design.* Four between-subjects conditions were created by pairing the rotational-motion cue with each of the four target types (i.e., rotational motion, translational motion, onset, and color). The four between-subjects conditions were crossed with three within-subjects cuing conditions. Cue conditions were created by varying the spatial relationship between cues and targets. In the 100% valid-cue condition, cues and targets always appeared at the same outer box. In the 100% invalid-cue condition, targets always appeared in a box other than where cues had appeared. In the neutral condition,

circles appeared around each box during the cuing event, but none shifted position.

The three within-subjects cue conditions were presented in separate blocks of trials, with order of presentation counterbalanced across subjects. With cue conditions blocked, subjects knew the validity of the cue before each trial with absolute certainty. Each subject was randomly assigned to one of the six possible cue-condition orders. Each cue condition consisted of two contiguous 72-trial blocks. Target identity and location were chosen randomly with the constraint that each character appear as a target at each location equally often within each block. In the 100% invalid condition, cue positions were chosen with the constraint that cues appear equally often in each of the three possible nontarget locations for each possible target location. In the motion-target and color-target conditions, the identity of the characters (X or =) that appeared in the three nontarget boxes was chosen randomly on each trial.

*Procedure.* Subjects were tested in one 60-min session in a dimly lit laboratory room. Written and oral descriptions of the stimuli and procedures were provided to familiarize subjects with the task. Subjects were fully informed of the blocked arrangement of the cue conditions and were encouraged to make use of this

knowledge if possible (e.g., to completely ignore the cue in the 100% invalid condition). Subjects were instructed to respond "as quickly as you can but also to make as few errors as possible." Maintaining fixation on the central cross was highly stressed and subjects were told that shifting their eyes would impair overall performance.

At the beginning of each block of trials, a message on the CRT screen indicated which of the three cue conditions (100% valid, 100% invalid, or neutral cue) would appear in that particular block of trials. Subjects pressed the "enter" key to start the block. At the end of a block, the message "rest" appeared on the display screen.

At the beginning of each individual trial sequence, the central fixation cross and four surrounding boxes were presented for 500 ms. The 120-ms cue display was presented following a 100-ms warning blink of the fixation cross and a randomly varying foreperiod of either 1,000, 1,100, 1,200, 1,300, or 1,400 ms. The 120-ms target display was presented 50 ms after the cue display was extinguished and was followed by the return of the fixation display. The next trial sequence was initiated 1000 ms after a response was made. Phenomenally, the four display boxes and the fixation cross appeared to remain on the CRT screen for the duration of each trial, as well as the intertrial interval. The stimulus onset asynchrony (SOA) between cue and target was 170 ms. Thus, although not formally monitored, eye movements were unlikely.

Subjects made a forced-choice target identification by pressing the period and 0 keys on the numeric keypad of the keyboard for X and = targets, respectively (the keys were appropriately labelled). Response time was measured from the onset of the target display in the color- and onset-target conditions, and from the onset of the second frame of the target display in the motion-target conditions. If a response was not initiated within 1,500 ms, an error was scored and the next trial sequence initiated. Incorrect responses elicited a 500-ms, 1000-Hz computer tone and were followed by a "buffer" trial with parameters drawn randomly from the set for that block. Response times for error and buffer trials were not included in the data analysis. To reduce the influence of any carry-over effects introduced by blocking cue validity, only data from the second block of trials in each condition were included in the data analysis.

## Results

Mean correct response times and error rates for each cue validity in each target property condition are shown in Figure 2. A 4 (target property)  $\times$  3 (cue validity) mixed analysis of variance (ANOVA) on the mean correct response times revealed main effects of target property,  $F(3, 68) = 6.88$ ,  $p < .001$ , and cue validity,  $F(2, 136) = 88.31$ ,  $p < .0001$ . The Cue Validity  $\times$  Target Property interaction was also significant,  $F(6, 136) = 15.62$ ,  $p < .0001$ .

Simple effects analyses revealed significant effects of cue validity in all target-property conditions: For rotational targets,  $F(2, 34) = 43.44$ ,  $p < .0001$ , translational targets,  $F(2, 34) = 50.61$ , onset targets,  $p < .0001$ ,  $F(2, 34) = 3.33$ ,  $p < .05$ , and color targets,  $F(2, 34) = 4.49$ ,  $p < .05$ . Tukey post hoc analyses ( $\alpha = .05$ ) established that relative to the neutral condition, 100% invalid rotational cues produced significant costs of 42 and 54 ms when paired with rotational- and translational-motion targets, respectively, and nonsignificant costs of 7 ms and 5 ms when paired with onset and color targets, respectively. Similarly, when the rotational-motion cues were 100% valid, significant benefits of 72 ms and 130 ms emerged for rotational and translational targets, respec-

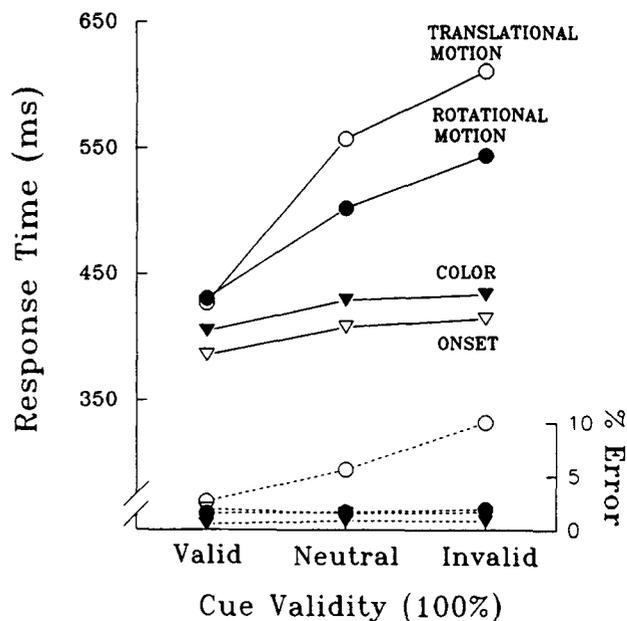


Figure 2. Average mean response times and error rates as a function of target property and cue validity in Experiment 1. In all conditions, target displays were preceded by a rotational-motion cue.

tively, and nonsignificant benefits of 22 and 24 ms for onset and color targets, respectively.

Overall error rate averaged 2.5%. The pattern of error rates across experimental conditions is similar to that found for response times. Errors and response times show a significant positive correlation,  $r(10) = .80$ ,  $p < .05$ , making a speed-accuracy trade-off unlikely.

## Discussion

The results of this experiment are straightforward: 100% invalid motion precues interfered with the processing of motion targets but not onset or color targets. The elimination of this interference when the identical precues appeared at the same location as the target (i.e., the benefits observed with 100% valid cues) suggests that the observed interference reflects changes in the spatial distribution of attention (i.e., attentional capture), rather than some more central, nonspatial interference effect.

These results have several important implications for theories of attentional control. First, they provide additional support for contingent involuntary orienting, showing that apparent motion will capture attention if subjects are searching for targets signaled by motion but not if they are searching for color or onset targets. Second, the significant costs for both rotational- and translational-motion targets suggests that the allocation system cannot be configured to respond to specific forms of apparent motion. This is analogous to the finding of Folk et al. (1992) that subjects were unable to set for specific color values. The absence of costs for onset targets, on the other hand, suggests that motion and abrupt onset, while both dynamic events, are treated as functionally

distinct by the attention allocation system. This casts doubt on the proposal of Folk et al. (1992) that attentional control settings are limited to static versus dynamic discontinuities by showing that attentional control settings can distinguish between two classes of dynamic discontinuity.

Finally, the results of Experiment 1 provide no support for the hypothesis that the contingent capture reported by Folk et al. (1992) resulted from an attentional set for field properties versus single items. Motion cues produced no evidence of attention capture when paired with color targets despite the fact that both were field displays (i.e., each consisted of a discontinuity in a set of simultaneously presented stimuli).

### Experiment 2

There is substantial evidence for the existence of two distinct processes for extracting motion information, each operating under unique stimulus conditions (for a review, see Petersik, 1989). As originally proposed by Braddick (1974), short-range apparent motion consists of the activation of low-level motion detectors that respond under conditions of small spatial displacements, short stimulus durations, and short ISIs. In contrast, long-range apparent motion consists of higher order perceptual activity that operates over relatively larger displacements, longer stimulus durations, and longer ISIs. These two types of apparent motion have also been shown to differ with respect to their attentional requirements (Dick, Ullman, & Sagi, 1987; Ivry & Cohen, 1990). Ivry and Cohen, for example, found that targets defined by short-range apparent motion tend to "pop-out" in a traditional visual-search task, suggesting that this form of apparent motion is processed preattentively. Long-range motion targets, on the other hand, yielded a linear increase in response time with display size, suggesting that the processing of long-range motion requires spatial attention.

Apparent motion for the cues in Experiment 1 was generated by successive ( $ISI = 0$ ), 40-ms presentations of cue elements displaced by 39.8 min of visual angle, a spatial displacement well within the range typically associated with long-range apparent motion. Thus, it is possible that the processing of apparent-motion cues in Experiment 1 was done at relatively high, postattentional levels, without activating systems that mediate attentional capture. Stimuli processed by the low-level, preattentive, short-range process may indeed produce involuntary attention shifts regardless of behavioral goals (i.e., attentional control settings). Experiment 1 was therefore replicated with cues defined within the parameters of short-range apparent motion to test whether short-range apparent motion would capture attention irrespective of behavioral goals.

### Method

**Subjects.** Fifty-four subjects, aged 18 to 21, participated in this study. Subjects were recruited and screened for acuity and color vision in the same manner as Experiment 1.

**Apparatus and stimuli.** The apparatus and stimuli were identical to those used in Experiment 1 except that the displacement of cue circles was reduced to 17.2' visual angle (measured from the

center of the circles in the successive displays). This value is very close to the 17.9' value used by Ivry and Cohen (1990) for short-range apparent motion.

**Design and procedure.** Because the translational and rotational target conditions in Experiment 1 yielded essentially the same results, only rotational targets were tested in Experiment 2. In all other respects, the design and procedure were identical to those used in Experiment 1.

### Results

Mean correct response times and error rates for each cue validity at each target property condition are shown in Figure 3. A 3 (target property)  $\times$  3 (cue validity) ANOVA on mean correct response time revealed significant main effects of target property,  $F(2, 51) = 25.17, p < .0001$ , and cue validity,  $F(2, 102) = 56.43, p < .0001$ , as well as an interaction between these variables,  $F(4, 102) = 22.56, p < .0001$ .

Simple effects analyses identified significant cue validity effects for motion targets,  $F(2, 34) = 65.53, p < .0001$ . Tukey tests confirmed that, relative to neutral cues, 100% invalid cues produced a significant 45-ms cost, and 100% valid cues produced a significant 77-ms benefit. The effect of cue validity was also significant for onset targets,  $F(2, 34) = 4.63, p < .02$ , but, as in Experiment 1, no significant costs or benefits (relative to the neutral condition) were associated with invalid or valid cues, respectively. There were no significant effects of cue validity for color targets,  $F(2, 34) = 2.33, p > .05$ . Overall error rate averaged 1.3%. As in Experiment 2, error rates were positively correlated with response time,  $r(7) = .73, p < .05$ .

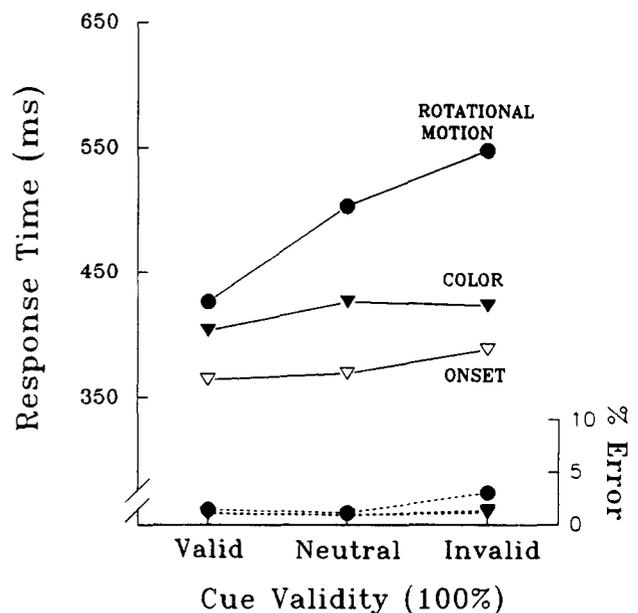


Figure 3. Average mean response times and error rates as a function of target property and cue validity in Experiment 2. In all conditions, target displays were preceded by a short-range, rotational-motion cue.

## Discussion

The results of this experiment are nearly identical to those of Experiment 1. Invalid motion cues interfered with the processing of motion targets but left the processing of color and onset targets unaffected. Even when the motion is of a type processed by low-level, preattentive processes (i.e., short-range motion), involuntary shifts of attention to cues exhibiting such motion remain contingent on the property signaling the location of the target. Moreover, the lack of costs in the onset-target condition replicates the functional dissociation between abrupt onset and motion found in Experiment 1.

## Experiment 3

In Experiments 1 and 2, we found significant costs and benefits for 100% invalid and 100% valid motion cues, respectively, only when targets were also signaled by apparent motion. This result is consistent with the hypothesis that attentional capture occurs only when the eliciting property matches an advance attentional set for the target property. When set for motion, motion cues captured attention; when set for onset or color, motion cues did not capture attention.

Alternatively, it could be argued that attention was, in fact, captured by motion cues in all target property conditions, but that the target discriminations in the onset and color conditions were so easy that the withdrawal of attention from the target location had very little measurable effect. Variations in cuing effects with target property may be a function of the difficulty of target discrimination rather than the relationship between the defining properties of cues and targets. The lack of significant benefits in the 100% valid condition for onset and color targets is consistent with this interpretation.

To address this possibility, we designed Experiment 3 as a test of four within-subject conditions, created by the factorial combination of color and motion targets with color and motion cues. If the costs for the motion conditions in Experiments 1 and 2 reflect greater difficulty in discriminating motion targets, then cuing effects should obtain for motion targets but not for color targets, regardless of cue type. If, however, the observed cuing effects reflect differential attentional control settings, then cuing effects should obtain only when targets are preceded by cues defined by the same property.

Cues in Experiment 3 appeared on every trial (the neutral cue condition was eliminated) but were uncorrelated with target location. Given four possible target locations, the cue was valid on 25% of the trials and invalid on the remaining 75%. The low cue validity provides subjects with little incentive to voluntarily shift attention to the location of the cue. Thus, any difference in response time as a function of cue validity indicates an involuntary shift of attention (for designs with similar logic, see Jonides & Yantis, 1988; Müller & Rabbitt, 1989; Yantis & Jonides, 1984).

## Method

**Subjects.** Twenty new Villanova University undergraduates participated; they were recruited under the same conditions and were given the same visual screening tests as subjects in the previous experiments.

**Apparatus.** The apparatus was identical to that used in the first two experiments except that the monitor, which was placed inside a black wooden viewing box, was 50 cm from lenseless goggles attached to a porthole in the front of the box. All but the screen of the monitor was occluded by a black baffle inside the box. The viewing box was used to ensure a constant viewing distance to the monitor and to eliminate any potential effects of peripheral stimuli.

**Stimuli.** A new color-cue stimulus was added to the motion-cue, motion-target, and color-target stimuli of Experiment 2. The color cue was identical to the neutral cue used in the first two experiments, except that one set of four circles surrounding one of the four boxes appeared in high-contrast red (IBM color designation No. 12). The box around which these red circles appeared was designated as the cued box.

**Design and procedure.** The four cue-target conditions created by crossing motion and color cues with motion and color targets were presented in separate blocks of trials. All subjects participated in all four conditions. Condition order was counterbalanced across subjects using a Latin square, and subjects were randomly assigned to one of four orders.

Ninety-six trials for each cue-property/target-property condition were presented in three contiguous blocks of 32 trials. Within a block, targets and cues appeared at each location equally often. Target location and cue location, however, were completely uncorrelated; the target appeared at the cued location on exactly one fourth of the trials (valid cue) and at uncued locations on three fourths of the trials (invalid cue). For a given target location, invalid cues appeared equally often at each of the three remaining locations.

The sequence of events was the same as in Experiments 1 and 2, but the timing of events was slightly modified to equate the effective cue-target SOAs, as well as the effective target durations, across conditions.<sup>2</sup> In the motion-cue/motion-target condition, timing was identical to that used in the motion-target conditions of the previous experiments. In the motion-cue/color-target condition, the cue display was followed by a 90-ms presentation of the fixation display and an 80-ms presentation of the target display. In the color-cue/motion-target condition, the cue display was presented for 80 ms, then the fixation display for 50 ms, followed by the 120-ms motion-target event. Finally, the color-cue/color-target condition consisted of an 80-ms presentation of the cue display, a 90-ms presentation of the fixation display, followed by an 80-ms presentation of the target display. Given these values, the effective cue-target SOA was 170 ms in all conditions, and the effective cue and target durations were 80 ms.

<sup>2</sup> In the first two experiments the main sequence of events in all conditions consisted of a 120-ms cue event and a return to the fixation display for 50 ms followed by a 120-ms target event. One could argue, however, that the effective "onset" of a motion cue or a motion target did not occur until 40 ms into the apparent-motion display sequence, when the display containing the displaced cue/target elements appeared. Assuming this timing scheme, the effective cue-target SOA on valid and invalid trials in the motion-target conditions (170 ms) was 40 ms longer than in the color- or onset-target conditions (130 ms). Moreover, the effective duration of targets in the motion condition was 40 ms shorter than in the color- or onset-target conditions.

Each block began with the presentation of a screen indicating which of the four cue-property/target-property conditions and which block of that condition was about to begin, followed by 14 warm-up trials. The first block of each condition was treated as practice. Response times for practice, warm-up, error, and buffer trials were not included in the data analysis. In all other procedural respects, the experiment was identical to the first two experiments.

## Results

Mean correct response times and error rates for valid and invalid trials at each combination of cue-property/target-property, pooled across blocks, are shown in Figure 4. Planned interaction comparisons consisting of 2 (cue validity)  $\times$  2 (cue property) ANOVAs were conducted at each level of the target property variable. For color targets, both cue property and cue validity produced significant main effects,  $F(1, 19) = 23.79, p < .0001$  and  $F(1, 19) = 19.26, p < .0003$ , respectively. More important, the interaction between these two variables was significant,  $F(1, 19) = 40.71, p < .0001$ . Pairwise comparisons revealed that color cues produced a significant 48-ms cue validity effect,  $t(19) = 7.81, p < .0001$ ; the effect of motion cues ( $-1$  ms) was not significant,  $t(19) = 0.26, p > .05$ .

For motion targets, there was a significant main effect of cue validity,  $F(1, 19) = 4.45, p < .05$ , as well as a significant Cue Validity  $\times$  Cue Property interaction,  $F(1, 19) = 6.78, p < .02$ . Pairwise comparisons revealed significant cue validity effects for motion cues (34 ms) but not for color cues ( $-8$  ms);  $t(19) = 2.77, p < .02$  and  $t(19) = 1.11, p > .05$ , respectively. Overall error rate was 2.3%. Error proportions were positively correlated with response times, although not significantly so,  $r(6) = .52, p > .05$ .

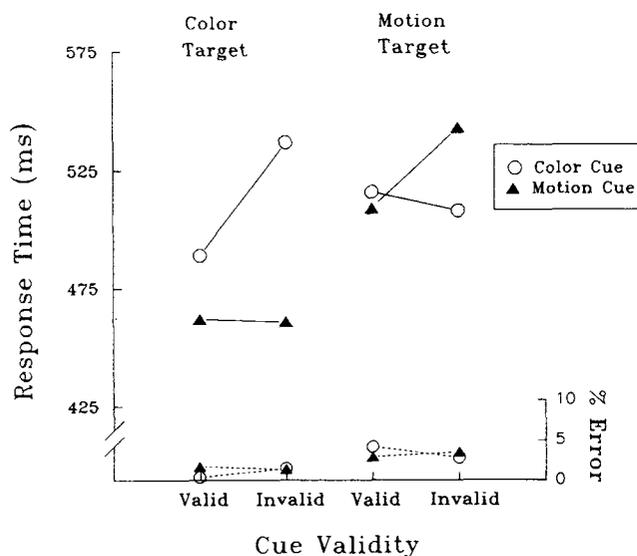


Figure 4. Average mean response times and error rates as a function of target property, cue property, and cue validity in Experiment 3.

## Discussion

The results of Experiment 3 confirm that cue validity effects are a function of the relationship between the cue property and target property rather than the difficulty of target discrimination. For motion targets, motion cues produced a validity effect and color targets did not. For color targets, color cues produced a validity effect and motion targets did not. Thus, validity effects are clearly dependent on a match between the cue and target property rather than on the discriminability of targets.

One might argue, however, that in the present paradigm, the contingent orienting hypothesis would predict a crossover interaction between cue validity and cue property for each target property condition. If a cue does not elicit a shift of attention (i.e., if the cue is essentially "neutral"), then response times for such trials should fall between the response times for valid and invalid trials on which attentional shifts are elicited. Neither target condition produced strong evidence for such an interaction. The crossover prediction, however, is based on the assumption that cues only affect the distribution of spatial attention. Peripheral cues and their relationship to target property may have measurable effects on later stages of processing that are independent of any effects associated with shifts of spatial attention. The apparent elevation of response times in the color-cue/color-target and motion-cue/motion-target conditions suggests that a match between cue and target properties produces not only an involuntary shift of attention, but a generalized distraction that is independent of attentional shifts. Similar results and conclusions have been reported by Remington et al. (1992). The important point is that the presence of such effects, while interesting in their own right, in no way invalidate our conclusions. The interaction between cue validity and cue property obtained in each target property condition provides strong evidence for contingent orienting, regardless of the ordinality of the interactions.

## Experiment 4

In Experiments 1 and 2 we found no effect of apparent-motion cues on abrupt-onset targets, suggesting that these two forms of dynamic discontinuity are functionally distinct with respect to attentional control settings. However, to conclude that motion and onset are truly independent, it is necessary to demonstrate a double dissociation; onset cues should not disrupt the processing of motion targets. Experiment 4 paired motion and onset cues with motion and onset targets to further explore the functional relationship between abrupt onset and apparent motion. If these two properties are completely independent with regard to attentional control, then a symmetric pattern of cuing effects, similar to that found in Experiment 3, should emerge.

## Method

**Subjects.** Twenty new subjects, recruited from the same pool and under the same conditions as in the previous experiments, participated in this study.

**Apparatus and stimuli.** Stimuli and apparatus were identical to those used in Experiment 3, except that color cues and color targets were replaced by onset cues and onset targets. Onset cues consisted of the fixation display with the addition of one set of four circles around one of the four boxes. Onset target displays were identical to those used in Experiments 1 and 2.

**Design and procedure.** The design and procedures of this experiment were identical to those of Experiment 3.

## Results

Mean correct response times and error rates for valid and invalid trials at each combination of cue-property/target-property, pooled across block, are shown in Figure 5. Planned interaction comparisons consisting of 2 (cue validity)  $\times$  2 (cue property) ANOVAs were conducted at each level of the target property variable. For onset targets, both cue property and cue validity produced significant main effects; response time to onset targets was faster when preceded by motion cues than by onset cues,  $F(1, 19) = 11.72, p < .01$ , and invalid cue produced longer response times than valid cues,  $F(1, 19) = 14.54, p < .01$ . The interaction between these two variables was also significant,  $F(1, 19) = 5.13, p < .05$ . Pairwise comparisons revealed that onset cues produced a significant 25-ms cue validity effect,  $t(19) = 4.80, p < .001$ , whereas motion cues produced a marginally significant 10-ms validity effect,  $t(19) = 1.93, p = .07$ .

For motion targets, there was a significant main effect of cue validity, with invalid cues producing longer response times than valid cues,  $F(1, 19) = 20.80, p < .001$ . Pairwise comparisons confirmed that both cue types produced significant validity effects,  $t(19) = 5.13, p < .001$  for the 45-ms effect of motion cues and  $t(19) = 2.52, p < .05$  for the 32-ms effect of onset cues. The main effect of cue property, as well as the Cue Validity  $\times$  Cue Property interaction, however,

were not significant,  $F(1, 19) = 0.02, p < .05$  and  $F(1, 19) = 2.25, p > .05$ . Overall error rate was 5.8%. Error rates were highly correlated with response times,  $r(6) = .92, p < .05$ .

## Discussion

Unlike the symmetric pattern of selectivity in attentional capture found with motion and color in the previous experiment, Experiment 4 suggests an asymmetric pattern of cuing effects between motion and onset. The effect of motion cues depended on target property; significant validity effects were found for motion targets and only marginally significant effects for onset targets, producing a significant interaction between cue property and cue validity. This result is consistent with the results of the onset- and motion-target conditions of Experiments 1 and 2. The effect of onset cues, on the other hand, did not depend on target property; significant validity effects for both motion and onset targets were obtained, with no hint of an interaction.

Assuming the observed asymmetry is indeed real, there are at least two possible explanations for its existence. First, it could be related to the unique relationship between the processing of abrupt onset and apparent motion. Apparent motion is a derivative of abrupt onset; it depends on the detection of at least two abrupt onsets occurring over a small time interval and spatial range. This hierarchical relationship between onset and apparent motion is supported by the results of behavioral studies involving such diverse paradigms as selective adaptation (Anstis, 1986) and visual search (Cavanagh, Arguin, & Treisman, 1990) and is consistent with studies of the underlying physiology (Livingstone & Hubel, 1988; Van Essen & Maunsell, 1983). If the processing of apparent motion is dependent on the detection of abrupt onsets, then an attentional set for motion may necessarily involve a set for onset. Since the relationship is hierarchical, however, the reverse is not necessarily true; an attentional set for onset need not imply a set for motion. Thus, the observed asymmetry may reflect constraints on attentional control related to the underlying structure of stimulus processing. Note that on this account, abrupt onset and motion still constitute two distinct attentional control settings; it is the nature of the task that constrains the selectivity of capture (i.e., pairing hierarchically related properties), not the range of control settings.

A second possibility is that the observed asymmetry is a function of differences in the relative salience of onset and motion stimuli. Recent work with static discontinuities by Theeuwes (1991a, 1992) suggests salience may indeed play a role in attentional capture. Specifically, Theeuwes found that the influence of an irrelevant discontinuity in one dimension (e.g., color) on search for a relevant discontinuity in a different dimension (e.g., shape) depended entirely on the relative salience of the two discontinuities. Interference by the irrelevant discontinuity occurred only when its salience was greater than the relevant discontinuity. The results of the present experiment may reflect a greater salience for onset stimuli than motion stimuli, yielding the observed asymmetry in attentional capture. Unlike the structural in-

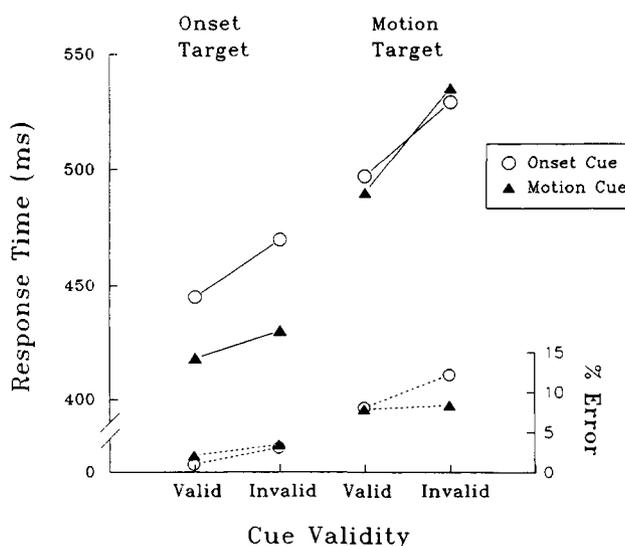


Figure 5. Average mean response times and error rates as a function of target property, cue property, and cue validity in Experiment 4.

terpretation discussed above, this account assumes that onset and motion require the same attentional control setting (i.e., for a dynamic discontinuity), but that in the present setting, capture is further influenced by the relative salience of the two discontinuities.

One might argue that a salience account is implausible on the grounds that apparent-motion cues themselves consist of two abrupt onsets (as well as the motion percept), and thus might be expected to produce a stimulus with greater salience than a single abrupt onset. The problem is that the first onset in an apparent-motion cue is accompanied by onsets at all three other locations (and thus enjoys no advantage in salience relative to the other locations), and the second onset (of the displaced circles) occurs so close in time to the first (within 40 ms) that its salience may be reduced. Furthermore, the apparent-motion cue occurs in the midst of a field of abruptly onset circles. This is quite different from an onset cue, which consists of the single onset of one set of circles at only one location.

### Experiment 5

We conducted the fifth experiment to distinguish between the structural and salience accounts of the asymmetry observed in Experiment 4. Our approach was to replicate the previous experiment, but to attempt to equate the relative salience or "strength" of the two cue types. According to the structural account, changing the relative salience of the two cue types should have no effect; an asymmetry in cuing effects should still obtain. According to the salience account, however, motion and onset cues with similar salience should produce similar effects; significant cuing effects (i.e., attentional capture) should emerge in all conditions.

### Method

**Subjects.** Twenty new subjects, recruited from the same pool and under the same conditions as in the previous experiments, participated in this study.

**Apparatus and stimuli.** The apparatus was identical to that used in Experiment 4. To equate the relative strength of the two cue types, several changes were made to the stimuli used in Experiment 4. First, sets of four white circles, arranged in the same diamond configuration used in the previous experiments, remained present around each of the four boxes throughout the experiment. Onset cues consisted of an abrupt, 80-ms presentation of four additional white circles just outside the corners of the cued box. Motion cues consisted of the simultaneous offset of the existing circles at the cued location and the onset of four new circles appearing at the same relative positions as in Frame 2 of the motion-cue displays used in the previous three experiments. After 40 ms, these new circles were offset simultaneously with the onset of the original set of circles. In all other respects, the stimuli were identical to those used in Experiment 4.

Note that for both cue types, the stimuli and events at noncued locations were identical. Moreover, in both cases, the cue was signaled by the abrupt onset of four new circles. The primary difference between the two was the offset of the original circles in the motion-cue condition, which resulted in apparent motion. Thus, it is reasonable to assume that the two cue types were much more

similar with respect to salience or strength than was the case in Experiment 4.

**Design and procedure.** The design and procedures were identical to those of Experiment 4. The effective cue-target SOA was 170 ms in all conditions.

### Results

Mean correct response times and error rates for valid and invalid trials at each combination of cue-property/target-property, pooled across block, are shown in Figure 6. Planned interaction comparisons consisting of 2 (cue validity)  $\times$  2 (cue property) ANOVAs were conducted at each level of the target property variable. For onset targets, cue validity yielded the only significant effect,  $F(1, 19) = 11.65$ ,  $p < .01$ . The Cue Validity  $\times$  Cue Property interaction did not reach significance,  $F(1, 19) = 1.07$ ,  $p > .10$ . Tests of the effect of cue validity at each cue property yielded significance in both cases; for the 15-ms effect with motion cues,  $t(19) = 2.10$ ,  $p < .05$ , and for the 22-ms effect with onset cues,  $t(19) = 3.71$ ,  $p < .05$ .

For motion targets, an identical pattern emerged. Cue validity produced a main effect,  $F(1, 19) = 33.29$ ,  $p < .001$ , and pairwise comparisons confirmed that the 58-ms effect for motion cues was significant,  $t(19) = 4.47$ ,  $p < .05$ , as was the 41-ms effect for onset cues,  $t(19) = 5.01$ ,  $p < .05$ . No other effects were significant. Overall error rate was 2.4%. Error rates were highly correlated with response times,  $r(6) = .87$ ,  $p < .05$ .

### Discussion

The results of this experiment are quite clear. There was no evidence of any selectivity in attentional capture between

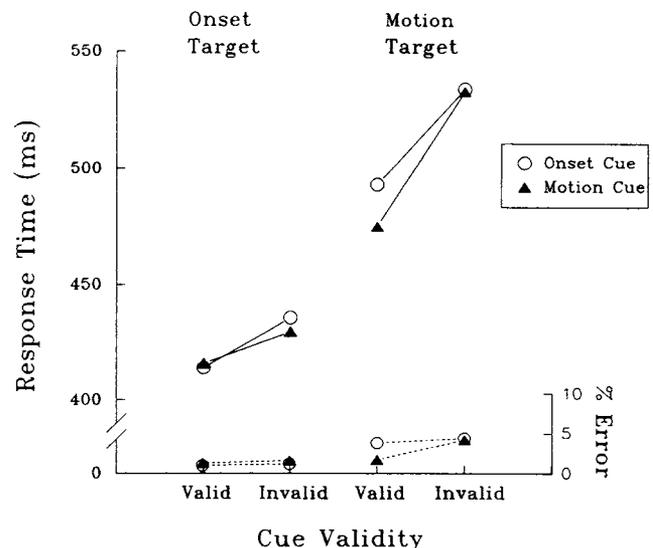


Figure 6. Average mean response times and error rates as a function of target property, cue property, and cue validity in Experiment 5.

apparent motion and abrupt onset. Apparent-motion cues captured subjects' attention when they searched for abrupt-onset targets and vice versa. Thus, Experiment 5 produced no evidence to support the strict structural account of the asymmetry observed in Experiment 4. Instead, the results suggest that with respect to attentional control settings, motion and onset are functionally equivalent. This is consistent with Folk et al.'s (1992) hypothesis that attentional control settings are broadly tuned to static versus dynamic discontinuities. The results also suggest that once the system has been set for dynamic discontinuities, capture is further contingent on the relative salience of the discontinuities, independent of the specific properties by which they are defined.

### General Discussion

The present series of studies were conducted to address two primary issues: (a) the generalizability of the contingent involuntary orienting hypothesis, and (b) the functional architecture of attentional control. With respect to the first issue, the results obtained with apparent-motion stimuli clearly provide further support for the hypothesis that involuntary shifts of attention are contingent on goal-related attentional control settings. Both long-range and short-range apparent-motion cues elicited involuntary shifts of attention, but only when the task required subjects to monitor for moving targets (Experiments 1–3), or for abrupt-onset targets. When the task required subjects to monitor for a discontinuity in color, these same cues produced no evidence of attentional capture. There may still exist unexplored properties that could override any attentional control setting, but we have ruled out a property with great potential to do so.

With respect to the architecture of attentional control, the present results provide support for the hypothesis that attentional control settings may be established for only very broad stimulus categories associated with the distinction between static and dynamic discontinuities. In all of the experiments reported here, as well as those reported by Folk et al. (1992), perfect selectivity in attentional capture was found when a static discontinuity in color was paired with dynamic discontinuities (i.e., abrupt onset or apparent motion). In contrast, little evidence of selectivity emerged between dynamic discontinuities defined along different feature dimensions (onset vs. motion) nor between discontinuities defined by different values on the same feature dimension (rotational vs. translational motion).

#### *The Role of Stimulus Salience*

Experiments 4 and 5 also provide evidence that stimulus salience plays an important role in attentional capture. The results indicate that once an attentional control setting has been established, attentional capture by irrelevant events consistent with that setting is further contingent on the salience of the irrelevant event relative to the target event. Specifically, if the salience of the irrelevant event is less than that of the target event, no attentional capture will occur.

Theeuwes (1991a, 1992) has observed similar effects of stimulus salience in a visual-search paradigm. The interfering effect of a color singleton on search for a form singleton and vice versa was found to be dependent on the relative salience of the two discontinuities. Theeuwes has argued that attentional allocation is based solely on stimulus salience; attention is directed in a bottom-up fashion according to relative salience, with no role played by top-down factors. Our new findings, as well as those of Folk et al. (1992), do not support this hypothesis. Rather, the effects of salience seem limited to circumstances where the stimuli are subsumed under the same overarching attentional control setting (such as the pairing of motion and onset in Experiments 4 and 5). Theeuwes's results are quite consistent with ours if one makes the reasonable assumption that color and form singletons fall under the same attentional control setting (i.e., static discontinuity). Differences in salience cannot, however, account for the symmetric selectivity in attentional capture between color and motion found in Experiment 3. Selectivity based on relative salience can only result in an asymmetric pattern of interference. Thus, in contrast to Theeuwes's claims, the results of Experiment 3 are clearly consistent with top-down control over attentional capture in the form of attentional control settings.

We propose that the salience-based selectivity observed in Experiments 4 and 5 itself reflects a form of top-down control rather than purely bottom-up attention allocation. According to bottom-up models, salience values for each display location/object are calculated preattentively and attention is then allocated to locations in order of salience magnitude (e.g., Koch & Ullman, 1985; Theeuwes, 1991a, 1992). In our paradigm, however, the cue display always precedes the target display. Thus, according to these models, attention should always be allocated to the cue since, at the time of cue presentation, the cued location will always yield the highest salience signal. Assuming the cue and target displays are indeed coded as distinct temporal events, the only way to account for the absence of an attentional shift to the cue is to invoke some form of top-down control. For example, if the cue event is consistently less salient than the target event, subjects may be able to adjust a "salience threshold" such that only those discontinuities with salience equal to or greater than the target event would capture attention. Such a mechanism would produce precisely the pattern of results found in Experiments 4 and 5.<sup>3</sup> Again, we emphasize that such a strategy cannot account for the symmetric selectivity found in Experiment 3; the strategy would presumably only be instantiated when broadly tuned dimensional control settings fail.

#### *Attentional Control Settings and Guided Search*

The notion that attention allocation is influenced by top-down goal-related factors, as suggested here, is also a central aspect of a class of recent models of conjunctive visual search (e.g., Bundesen, 1990; Cave & Wolfe, 1990; Duncan &

<sup>3</sup> Note that such a strategy can also account for the patterns of interference in Theeuwes (1991a, 1992).

Humphreys, 1989; Treisman & Sato, 1990). According to these models, attention is "guided" to display locations through activation of task-relevant properties or inhibition of irrelevant properties (Driver, McLeod, & Dienes, 1992). Are the guidance mechanisms proposed to operate during conjunctive search the same as the attentional control settings proposed to regulate attentional capture? Evidence from conjunctive search tasks suggests that top-down guidance can operate at the level of specific feature values such as particular colors, forms, or orientation (Treisman & Sato, 1990; Wolfe, Cave, & Franzel, 1989). The patterns of interference in our spatial cuing tasks, however, suggest that attentional control settings are limited to very broad stimulus categories. Thus, although the existing data do not provide a definitive answer, we speculate that the two classes of phenomena reflect the operation of independent control systems.

### *Visual Pathways and the Locus of Attentional Control*

We have argued that top-down influence over attentional capture is limited to two broadly tuned control settings, namely static discontinuities versus dynamic discontinuities. Such a distinction is consistent with anatomical, physiological, and psychophysical evidence for the existence of two primary, parallel pathways in the processing of visual information (e.g., Livingstone & Hubel, 1988; Van Essen & Maunsell, 1983). The magnocellular geniculate pathway is composed of cells with high contrast sensitivity and fast temporal resolution but low color selectivity and spatial resolution. As such, this pathway is uniquely adapted to processing the dynamic discontinuities in luminance such as those associated with abrupt onset and apparent motion. In contrast, cells in the parvocellular geniculate pathway are characterized by high color selectivity and spatial resolution but low contrast sensitivity and temporal resolution. This pathway would therefore carry information about sustained discontinuities across space, such as color singletons.

As the two parallel pathways project into cortex, however, they subdivide into distinct anatomical and functional branches. As an example, cortical area MT, which receives projections from the magnocellular pathway, is specialized for the processing of motion information (Livingstone & Hubel, 1988). Individual cells in this area even show selectivity to the direction and velocity of movement (Baker, Petersen, Newsome, & Allman, 1981). The apparent coarse tuning of attentional control settings observed in the present experiments as well as those of Folk et al. (1992) suggest that attentional control settings are most likely instantiated at the level of the geniculate branches of the magnocellular and parvocellular pathways rather than their highly selective cortical projection sites.

This speculation must be treated with some caution, however, because differences in the nature of information carried by early visual pathways are correlated with differences in stimulus "similarity." It is quite plausible, therefore, to assume that attentional control settings act on some similarity space, rather than directly on low-level visual system pathways. For example, the ability to selectively control capture

by a given stimulus may depend on the "distance" between the stimulus and the target in such a similarity space, independent of the dimensions on which similarity is based. Of course, since attention cannot logically be captured by properties that themselves require attention to process, such a similarity space must be defined in terms of preattentively available stimulus attributes, and might thus be expected to reflect the structure of early, preattentive stimulus processing. The relationship between visual pathways, the functional architecture of stimulus processing, and attentional control processes promises to be an exciting and fruitful research domain.

### *Conclusions*

This series of studies establishes that apparent motion, like color and onset, will capture attention, but only when the task requires monitoring for a dynamic discontinuity. This provides further empirical support for the notion of contingent involuntary orienting. In addition, the lack of selectivity in attentional capture between different forms of apparent motion, as well as between abrupt onset and apparent motion, supports the hypothesis that attentional control settings are broadly tuned, distinguishing only between static and dynamic discontinuities. Finally, the results suggest that an additional form of top-down control, based on stimulus salience, may operate under certain circumstances to further gate attentional capture.

Attentional capture is a robust and adaptively advantageous phenomenon. The ability to modulate such capture, however, is just as advantageous. The picture that is emerging from these studies is that the ability to modulate attentional capture is much more extensive than previously believed. Clearly, further research is needed to understand the full range of strategies available for attentional control as well as to model the underlying mechanisms.

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