
Shifts of Visual Attention to Multiple Simultaneous Location Cues

RICHARD D. WRIGHT *Simon Fraser University*

Abstract Single and simultaneous multiple location cues were presented a brief period of time before the onset of targets that observers were required to identify. Single and multiple cueing effects were similar, even when targets were presented at locations "in between" pairs of cues. This implies that pairs of direct stimulus cues are not processed by an attentional focus of variable spatial extent that encompasses both cued locations. If this were the case, then targets presented in between cued locations would fall within such an attentional focus and identification response times should have been reduced. The increase in these response times that actually occurred when a target was presented at uncued locations in between a pair of cued locations suggests that pairs of cued locations are encoded independently by an operation called spatial indexing. A multiple indexing proposal and its role in mediating visual attention shifts initiated by direct stimulus cues is described.

A visual attention shift can be triggered reflexively by an abrupt-onset stimulus or initiated voluntarily after interpretation of a symbolic cue about where to "aim" attention. Shifts initiated by abrupt-onset stimulus cues (peripheral cues) and by symbolic information cues (central cues) are stimulus-driven and goal-driven respectively (e.g., Wright & Ward, 1994). Most attempts to describe the mechanism mediating these shifts have been based on the assumption that there is a unitary focus of attention (e.g., Eriksen & St. James, 1986; Jonides, 1980; LaBerge & Brown, 1989; Posner, Snyder, & Davidson, 1980). The primary support for this assumption is data from double-location-cue experiments. These experiments typically involve an information cue (i.e., a symbolic cue) about two locations at which the target has a high probability of occurring. After voluntary interpretation of this cue, observers appear to be unable to divide their attention into two foci and attend simultaneously to both expected target locations (e.g., Kiefer & Siple, 1987; McCormick & Klein, 1990; Posner et al., 1980). On the other hand, the results of several studies indicate that the attention shift mechanism also has

the capacity to encode attentional priorities about more than one location at a time and that a shift can be triggered to one of these locations in a stimulus-driven manner (e.g., Yantis & Johnson, 1990; Yantis & Jonides, 1990). This suggests that even if we can only attend to one location at a time, we also can encode and maintain information about other locations.

One unitary focus model in which information about several locations is simultaneously encoded is based on the assumption that "attentional resources" accumulate at corresponding locations in a representation of the visual field (LaBerge & Brown, 1989). In particular, "peaks" of resource accumulations form in response to abrupt onsets of stimuli. When the level of activation at a particular peak exceeds a threshold value, a channel of focussed attention is then said to be opened up at its location. In this way, several locations within the representation can be simultaneously processed and a unitary focus of attention can be shifted to the one with the highest activation level. Another indication of simultaneous encoding of multiple locations is our ability to keep track of several objects while attention is focussed elsewhere, and to do so even while these objects move randomly and independently (Pylyshyn, 1989; Yantis, 1992). One possible explanation for this ability is that spatial place tokens are dynamically bound to each of the objects to provide signals about their locations (Pylyshyn, 1989). The implication that place tokens or indexes underlie our capacity to encode and maintain information about several locations led Wright and Ward (1994) to propose that spatial indexes can be allocated to the locations of one or more abrupt-onset stimuli, and that the index with the strongest signal can trigger a stimulus-driven attention shift to its location (see also, Yantis & Johnson, 1990; Yantis & Jonides, 1990).

Wright and Ward (1994) have described the role of spatial indexing as signaling the locations of new abrupt-onset stimuli and maintaining information about the locations of other stimuli (see also, Wright & Ward, 1993). In addition, indexes can be allocated in a stimulus-driven or in a goal-driven manner, and there appears to be approximately four of them (cf. Müller & Humphreys, 1991; Pylyshyn, 1989; Yantis & Johnson, 1990; Yantis & Jonides, 1990). According to Wright and Ward (1994), spatial indexing's only role is to provide *location* information to subsequent visual processes, and a shift of visual attention to an indexed location can be triggered if attention is not actively focussed or engaged elsewhere.

The claim that multiple locations can be indexed and that one of the index signals can trigger a stimulus-driven attention shift is consistent with the following prediction: If a pair of stimulus cues is simultaneously presented in a target-identification task, the results should indicate that both cued locations are indexed and that response times are reduced if a target is presented at either location (and lengthened if the target is presented elsewhere). Moreover, this result should be obtained regardless of whether the cues are presented at

adjacent locations or at *nonadjacent* locations on either side of potential target locations.

An experiment has been conducted in which the response-time costs and benefits of single and adjacent double stimulus cueing were compared (Henderson, 1991). Costs and benefits were less pronounced with the adjacent double cue.¹ I tentatively call two explanations of this finding the *variable focal extent proposal* and the *multiple indexing proposal*. The variable focal extent proposal posits that a single focus of attention can encompass both cued locations at the same time or can decrease in spatial extent and encompass only a single cued location. Decreases in this spatial extent are said to lead to corresponding increases in the concentration of attentional resources (e.g., Eriksen & St. James, 1986). As a result, the concentration of resources would be greater at a single-cue location than when encompassing a pair of cued locations and, therefore, response-time costs and benefits should be more pronounced with single cueing. The multiple index proposal holds that spatial indexes can be allocated to the locations of one or more stimulus cues independently of focussed attention. Then, if attention is not actively engaged elsewhere, a shift is triggered to the location of the index with the strongest signal. As a result, response-time costs and benefits should be obtainable with multiple simultaneous stimulus cues depending on cue validity. While both proposals account for adjacent double cueing effects, the variable focal extent proposal cannot account for similar effects obtained when targets appear at uncued locations "in between" nonadjacent cued locations. In particular, the locations of such targets would be considered to be within the region of attentional focus and, therefore, according to the variable focal extent proposal, response times should be reduced on these invalid cue trials. The multiple indexing proposal, on the other hand, does account for such a finding because the cued locations are encoded independently. Therefore, response times for targets presented at intervening locations should not be reduced because they are not said to be within a region of attentional focus that encompasses both cued locations and all locations in between.

The first experiment was conducted to examine the effects of adjacent double cueing on target identification response times. The second was conducted to determine whether similar results would be obtained with nonadjacent double cueing. It was expected that the findings would indicate that unitary attentional focus models are controlled in part by multiple spatial indexing.

Experiment 1

METHOD

Fourteen Simon Fraser University students participated in this experiment. All

¹ Henderson (1991) referred to the single and adjacent double-cue conditions as "small" and "large" cue conditions respectively.

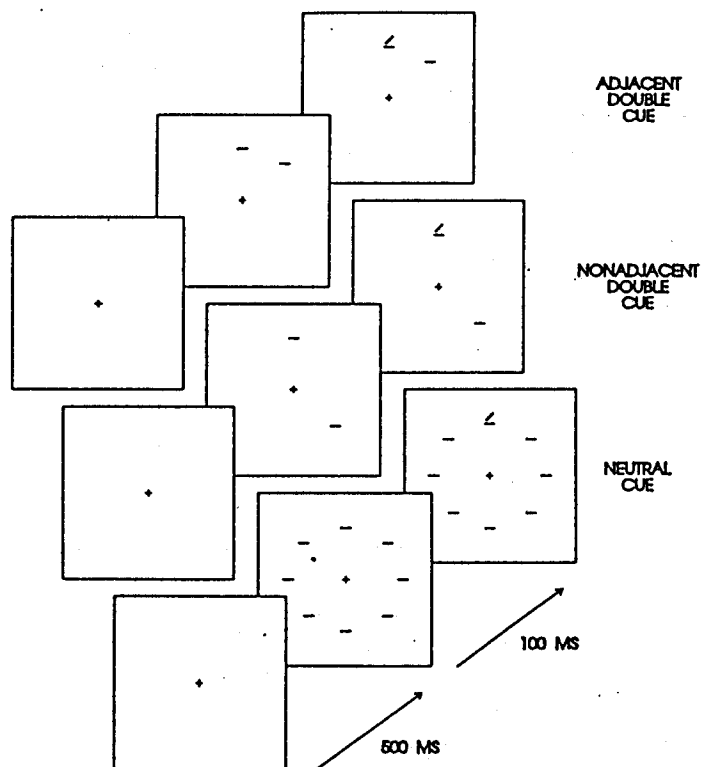


Fig. 1 Examples of stimulus displays used in each experiment. Cues were presented at one or two of the eight possible target locations in the circular array.

subjects were unaware of its purpose and all had normal or corrected-to-normal vision. Stimuli were displayed on a colour monitor at a distance of 50 cm. Experimental control, timing, and data collection were carried out with a microcomputer interfaced to two response buttons (Wright & Dawson, 1988). A white ($0.76 \times 0.76^\circ$) fixation cross remained visible throughout the experiment in the centre of a black (unlit) computer screen. Each trial began with a 500 ms delay followed by the presentation of one or two location cues. These were white ($0.76 \times 0.12^\circ$) horizontal lines presented at potential target locations. After another 100 ms delay, a white ($0.76 \times 0.76^\circ$) target was presented at one of eight locations arranged in a circular array and separated by 5.7° (see Figure 1). The target was a diagonal line oriented either from bottom-left to top-right, or from bottom-right to top-left. A 100 ms cue-target-onset asynchrony (CTOA) was used because this appears to be the interval at which stimulus cues pull attention to their locations most effectively (Cheal & Lyon, 1991; Müller & Findlay, 1988; Shepard & Müller, 1989). It is also short enough to preclude the possibility that a saccadic eye movement (regular or express) was made to the cued location before the target's onset (see e.g., Fischer & Weber, 1993).

There were five cue conditions. Single-valid cueing was simply the presentation of a cue at the impending target's location. Double-valid cueing was the presentation of two cues at adjacent positions within the circular stimulus array with one of the cues at the target location. Single-invalid cueing was the presentation of a cue at a nontarget location with the constraint that there be at least one "empty" position in the array between the cue and target (i.e., at least 10° between the cue & target). Double-invalid cueing was the presentation of two adjacent cues at nontarget locations with at least one empty position between these cues and the target. Neutral cueing was the presentation of cues at all eight positions to provide a signal about the target's impending onset but not its location. Each type of trial was equally likely and trial presentation order was completely random.

Observers were required to fixate their eyes on the centre of the display throughout the experiment. They were also required to indicate as quickly and as accurately as possible whether the target was a bottom-left/top-right or a bottom-right/top-left diagonal line by pressing one of two buttons. They received 40 practise trials followed by 720 data trials. In addition, 360 catch trials with a 1500 ms CTOA were randomly interspersed among the other trials to reduce response anticipation errors.

RESULTS

A repeated measures ANOVA was carried out on the mean correct response times of each subject for each condition (single-valid, double-valid, neutral, double-invalid, & single-invalid cue). All response times less than 100 ms or greater than 1000 ms were removed as outliers prior to the analysis, as were the remaining correct response times three standard deviations greater than or less than the mean response time for a particular condition. The results of the analysis indicated that response times were affected by cue type, $F(4,52) = 39.6$, $MS_e = 116.2$, $p < .0001$. Paired comparisons of means were carried out and the Newman-Keuls critical difference at the $p < .05$ level ranged from 8.2 to 11.5 ms for two to five means. All pairs of means differed significantly at either the $p < .05$ level or the $p < .01$ level except those for the double-invalid cue and single-invalid cue conditions (see Figure 2a). Therefore, mean response times were significantly faster in the valid cue conditions than in the neutral cue condition, and significantly faster in the neutral cue condition than in the invalid cue conditions. Moreover, response times were significantly faster in the single-valid cue condition than in the double-valid cue condition.

Another repeated measures ANOVA was carried out on the mean error rates of each subject for each condition after trials involving response-time outliers had been removed. Cue type also affected error rates, $F(4,52) = 4.1$, $MS_e = 14.8$, $p < .01$. Paired comparisons of means were carried out and the Newman-Keuls critical difference at the $p < .05$ level ranged from 2.9 to

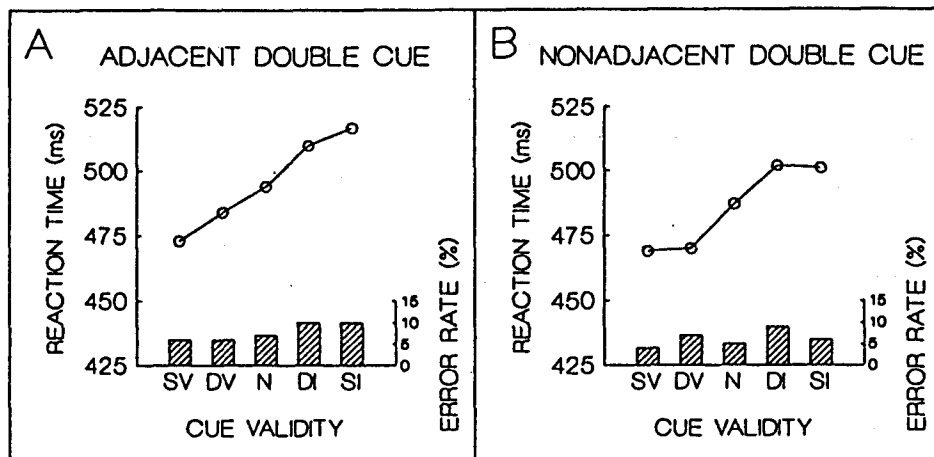


Fig. 2 (a) Mean response times and error rates for single-valid (sv), double-valid (dv), neutral (n), double-invalid (di), and single-invalid (si) cue conditions in Experiment 1. (b) Mean response times and error rates for each cue condition in Experiment 2.

4.1% for two to five means. Mean error rates were significantly lower for valid cue conditions than for invalid cue conditions, indicating that a speed-accuracy tradeoff did not occur.

DISCUSSION

The results of this experiment indicate that response-time costs and benefits can be obtained with single and adjacent double cueing. The benefits produced by the latter, however, were less pronounced, which is consistent with previous data (Henderson, 1991). The variable focal extent proposal accounts for this finding by holding that adjacent double cues were processed by a unitary attentional focus with a larger spatial extent (and therefore a lower concentration of resources) than that which processed the single cues. In other words, the difference in extremeness of response-time benefits in the single and adjacent double cueing conditions may be due to a difference in resource concentration. The multiple indexing proposal also accounts for this finding but an additional assumption is required. Response-time benefits on adjacent double-cue trials may be less pronounced than on single-cue trials because the former involves the allocation of a single spatial index to a position midway between the two cued locations. This is reasonable given the low spatial resolution of the early visual system's feature maps. Thus, on double-cue trials, neither cued location corresponds exactly to the indexed location but there is an exact correspondence between the cued and indexed locations on single-cue trials. A similar sort of proposal has been referred to as the "midlocation placement strategy" (Klein & McCormick, 1989, p. 246). If "midlocation" indexing of adjacent double cues is carried out, then the less than exact correspondence of the indexed location and the cued locations could produce response-time costs and benefits that are not as pronounced as

those yielded by single cues. This idea will be discussed again later in the article.

Experiment 2

A more direct test of the two proposals was carried out by repeating the previous experiment with nonadjacent double cues. The variable focal extent proposal holds that response times will be reduced for targets presented at locations between the cues because these targets fall inside a focus of attention encompassing both cued locations. On the other hand, the multiple indexing proposal holds that response times will be lengthened for targets presented at these uncued locations because the cued locations are processed independently. The latter result would indicate that multiple stimulus cue encoding does not involve the operation of a unitary attentional focus.

METHOD AND RESULTS

The procedure was identical in all ways, including number of subjects, to that of the first experiment, with the exception that nonadjacent double cues were presented instead of adjacent double cues. Nonadjacent double cueing involved the constraint that there be at least two empty positions in the stimulus array in Figure 1 between the pair of cues (i.e., 14°).

A repeated measures ANOVA was carried out on the mean correct response times of each subject for each condition (single-valid, double-valid, neutral, double-invalid, & single-invalid cue). Response-time outliers were removed in the same manner as in Experiment 1 prior to the analysis. The results indicated that response times were affected by cue type ($F(4,52) = 31.5$, $MS_e = 114.4$, $p < .0001$). Paired comparisons of means were carried out and the Newman-Keuls critical difference at the $p < .05$ level ranged from 8.1 to 11.4 ms for two to five means. Mean response times were significantly faster in the valid cue conditions than in the neutral cue condition (487 ms), and significantly faster in the neutral cue condition than in the invalid cue conditions (see Figure 2b). Single-valid cue (469 ms) and double-valid cue (470 ms) response times, however, were not significantly different. Neither were single-invalid cue (501 ms) and double-invalid cue (502 ms) response times.

Another repeated measures ANOVA was carried out on the mean error rates of each subject for each condition after trials involving response-time outliers had been removed. As in the first experiment, cue type affected error rates ($F(4,52) = 7.2$, $MS_e = 5.5$, $p < .01$). Paired comparisons of means were carried out and the Newman-Keuls critical difference at the $p < .05$ level ranged from 1.8 to 2.5% for two to five means. The mean error rate of the double-invalid cue condition was significantly higher than that for both valid cue conditions, the neutral cue condition, and the single-invalid condition. This indicates that a speed-accuracy tradeoff did not occur.

DISCUSSION

The results of this experiment indicate that equivalent response-time costs and benefits were obtained with single and nonadjacent double cueing. This finding does not support the variable focal extent proposal because costs occurred for targets that were presented at locations between the nonadjacent cues. The multiple index proposal accounts for the finding more parsimoniously because these costs suggest that each cued location is processed independently. If so, then such targets at uncued locations between cued locations will be responded to in the same manner as targets presented at other uncued locations (and targets at uncued locations in the single-cue condition). The variable focal extent proposal also cannot account for the equivalence of single-cue and nonadjacent-double-cue costs and benefits. The larger focus directed to a pair of nonadjacent cues is, by hypothesis, characterized by a lower concentration of attentional resources than the smaller focus directed to single cue locations. Therefore, in order for this proposal to be consistent with the results, the nonadjacent double-cue costs and benefits should have been less pronounced than those for single cues.

The multiple index proposal accounts for the results by positing that each of the two cued locations has a spatial index allocated to it and that both indexes have the capacity to summon attention. When a target is presented at one of these locations 100 ms after cue onset, response times are facilitated because both cued locations have already been encoded as potential shift destinations. On the other hand, when a target is presented at one location after a pair of cues has been presented elsewhere, response times are inhibited relative to the neutral cue condition because locations other than the target location have been encoded as potential shift destinations. The difference between the Experiment 1 and 2 results may be due to the allocation of a single index midway between adjacent cued locations in the first experiment as opposed to the allocation of separate indexes to nonadjacent cued locations in the second experiment. Pairs of nonadjacent cued locations were always at least 14° apart and therefore were unlikely to be marked with a single index as proposed when considering adjacent double cueing. In other words, the indexed locations and cued locations may be in exact correspondence in the second experiment, thereby making double cueing more effective than in Experiment 1.

GENERAL DISCUSSION

The results of the experiments indicate that similar response-time costs and benefits can be obtained with single and multiple simultaneous location cueing. Our capacity to simultaneously encode other locations besides the one currently attended to, however, is not inconsistent with unitary attentional focus models. In particular, previous research indicates that when a double information cue is presented (i.e., a symbolic cue about two locations), a

unitary focus appears to be shifted to only one of the expected target locations (e.g., McCormick & Klein, 1990; Posner et al., 1980). On the other hand, the current research involved stimulus cues. Wright and Ward (1994) have claimed that when stimulus-driven shifts occur, a unitary focus is shifted reflexively (if attention is not actively engaged) to the location of the strongest index signal and perhaps as many as four objects can be indexed. Thus, the difference between previous results and the current results may be attributable to the type of cue used to initiate the shifts. More specifically, information cueing may initiate a voluntary shift of a unitary attentional focus. Stimulus cueing appears to initiate spatial indexing of the cued location(s) that, in turn, can trigger a shift of the unitary focus to one of them.²

Therefore, an indexing account of multiple costs and benefits is not inconsistent with proposals that there is a unitary attentional focus. As proposed elsewhere (Wright & Ward, 1994), indexes are not attentional resources in a literal sense. Their role is to serve as anchor points for shifts of a unitary attentional focus. They are the means by which attention shift destinations are determined and shifts are triggered in a stimulus-driven manner. Therefore, multiple cueing effects do not invalidate unitary attentional focus models. Indexes provide location information only and can do so independently of attentional focus.

The multiple indexing proposal is also consistent with a related finding involving inhibition-of-return. This phenomenon occurs when the presentation of one stimulus cue is followed approximately 200 ms later by the presentation of a second stimulus cue at a different location. If, after a further 200 ms elapses, a target is then presented at the location of the first cue, detection response times will be inhibited relative to those for targets presented elsewhere. The visual system appears to "tag" the first cued location in such a way that temporarily inhibits processing there. We have found that inhibition-of-return will also occur at the locations of *two* simultaneously presented stimulus cues if they are followed 200 ms later by a third stimulus cue at a different location and then a target 200 ms after that at one of the first two cued locations (Wright & Richard, 1993). This multiple inhibition-of-return has been reported by others (e.g., Posner & Cohen, 1984, p. 539) and suggests that information about the locations of the first two cued locations is encoded and maintained while the third cue and then the target are presented. The maintenance of information about the locations of the first two cues may be carried out in the same manner as suggested in the current experiments – by the allocation of spatial indexes to their locations.

² While indexes can be allocated in a stimulus-driven or in a goal-driven manner, the proposal described applies only to stimulus-driven attention shifts. This is not meant to imply that indexing does not play a role in goal-driven shifts. This issue is discussed elsewhere in more detail (Wright & Ward, 1993, 1994).

In general, the results of the experiments indicate that encoding of stimulus cue locations can occur independently of operations of a unitary attentional focus. When a stimulus-driven attention shift is reflexively initiated to a cued location, the focus of attention cannot be aligned with that location until the shift mechanism "knows" where it is. Therefore, the initial stages of stimulus cue location encoding are a precursor to the attention shift. Given the nature of multiple spatial indexing, this operation allows us to account for stimulus-driven attention shift phenomena involving more than one location without resorting to proposals such as "splitting the beam of attention."

This project was supported by Natural Sciences and Engineering Research Council of Canada Grant 133551 and presented in May 1993 at the Third West Coast Attention Conference in Eugene, Oregon. I am grateful to Lawrence Ward, Steven Yantis, Robert Rafal, Kimron Shapiro, and Christian Richard for their thoughtful comments, and to Christian Richard for his assistance conducting the experiments and preparing the figures. Address correspondence to Richard Wright, Department of Psychology, Simon Fraser University, Burnaby, B.C., Canada, V5A 1S6 or via E-mail (rwright@sfu.ca).

References

- Cheal, M., & Lyon, D.R. (1991). Central and peripheral precueing of forced-choice discrimination. *Quarterly Journal of Experimental Psychology*, *43A*, 859-880.
- Eriksen, C.W., & St. James, J.D. (1986). Visual attention within and around the field of focal attention: A zoom lens model. *Perception & Psychophysics*, *40*, 225-240.
- Fischer, B., & Weber, H. (1993). Express saccades and visual attention. *Behavioral & Brain Sciences*, *16*, 553-610.
- Henderson, J.M. (1991). Stimulus discrimination following covert attentional orienting to an exogenous cue. *Journal of Experimental Psychology: Human Perception & Performance*, *17*, 91-106.
- Jonides, J. (1980). Towards a model of the mind's eye's movement. *Canadian Journal of Psychology*, *34*, 103-112.
- Kiefer, R.J., & Siple, P. (1987). Spatial constraints on the voluntary control of attention across visual space. *Canadian Journal of Psychology*, *41*, 474-489.
- Klein, R., & McCormick, P. (1989). Covert visual orienting: Hemifield activation can be mimicked by zoom lens and midlocation placement strategies. *Acta Psychologica*, *70*, 235-250.
- LaBerge, D., & Brown, V. (1989). Theory of attentional operations in shape identification. *Psychological Review*, *96*, 101-124.
- McCormick, P., & Klein, R. (1990). The spatial distribution of attention during covert visual orienting. *Acta Psychologica*, *75*, 225-242.

- Müller, H.J., & Findlay, J.M. (1988). The effect of visual attention on peripheral discrimination thresholds in single and multielement displays. *Acta Psychologica*, 69, 129-155.
- Müller, H.J., & Humphreys, G.W. (1991). Luminance-increment detection: Capacity-limited or not? *Journal of Experimental Psychology: Human Perception & Performance*, 17, 107-124.
- Posner, M.I., & Cohen, Y. (1984). Components of visual orienting. In H. Bouma & D.G. Bouwhuis (Eds.), *Attention & Performance, Vol. 10*. Hillsdale, NJ: Erlbaum.
- Posner, M.I., Snyder, C.R.R., & Davidson, B.J. (1980). Attention and the detection of signals. *Journal of Experimental Psychology: General*, 109, 160-174.
- Pylyshyn, Z.W. (1989). The role of location indexes in spatial perception: A sketch of the FINST spatial-index model. *Cognition*, 32, 65-97.
- Shepard, M., & Müller, H.J. (1989). Movement versus focusing of visual attention. *Perception & Psychophysics*, 46, 146-154.
- Wright, R.D., & Dawson, M.R.W. (1988). Using hardware interrupts for timing visual displays and reaction-time key interfacing on the Commodore 64. *Behavior Research Methods, Instruments, & Computers*, 20, 41-48.
- Wright, R.D., & Richard, C.M. (1993). *Inhibition-of-return of visual attention to multiple location cues*. Paper presented at the annual meeting of the Psychonomic Society, Washington, D.C.
- Wright, R.D., & Ward, L.M. (1993). Indexing and the control of express saccades. *Behavioral & Brain Sciences*, 16, 594-595.
- Wright, R.D., & Ward, L.M. (1994). *The control of visual attention*. Unpublished manuscript.
- Yantis, S. (1992). Multielement visual tracking: Attention and perceptual organization. *Cognitive Psychology*, 24, 295-340.
- Yantis, S., & Johnson, D.N. (1990). Mechanisms of attentional priority. *Journal of Experimental Psychology: Human Perception & Performance*, 16, 812-825.
- Yantis, S., & Jonides, J. (1990). Abrupt visual onsets and selective attention: Voluntary versus automatic allocation. *Journal Experimental Psychology: Human Perception & Performance*, 16, 121-134.