Perception & Psychophysics
1997, 59 (3), 389-403

On measuring selective attention to an expected sensory modality

CHARLES SPENCE
University of Cambridge, Cambridge, England

and

JON DRIVER
Birkbeck College, University of London, London, England

Perceptual judgments can be affected by expectancies regarding the likely target modality. This has been taken as evidence for selective attention to particular modalities, but alternative accounts remain possible in terms of response priming, criterion shifts, stimulus repetition, and spatial confounds. We examined whether attention to a sensory modality would still be apparent when these alternatives were ruled out. Subjects made a speeded detection response (Experiment 1), an intensity or color discrimination (Experiment 2), or a spatial discrimination response (Experiments 3 and 4) for auditory and visual targets presented in a random sequence. On each trial, a symbolic visual cue predicted the likely target modality. Responses were always more rapid and accurate for targets presented in the expected versus unexpected modality, implying that people can indeed selectively attend to the auditory or visual modalities. When subjects were cued to both the probable modality of a target and its likely spatial location (Experiment 4), separable modality-cuing and spatial-cuing effects were observed. These studies introduce appropriate methods for distinguishing attention to a modality from the confounding factors that have plagued previous normal and clinical research.

Mechanisms of attention allow us to concentrate on events of interest in the environment. Many researchers have suggested that sensory modality is one dimension along which selective processing can be mediated (e.g., Boulter, 1977; Hohnsbein, Falkenstein, Hoormann, & Blanke, 1991; Klein, 1977; Posner, Nissen, & Klein, 1976). That is, they claim that people can selectively direct their covert attention to just one modality, and as a result process events more efficiently in that modality than in situations where attention must be simultaneously divided between several sensory modalities or where attention is directed to another modality.

A further claim has been that abnormalities in selective attention to one modality versus another may underlie the cognitive deficits found in a number of clinical populations, including schizophrenics (Kraeplin, 1919; see Mannuzza, 1980, for a review), autistics (Ciesielski, Courchesne, & Elmasian, 1990; Courschesne et al., 1993), and cerebellar patients (Courchesne et al., 1993). Evidence apparently consistent with this view comes from numerous studies taken to show that these populations have an impaired ability both to focus their attention on a particular sensory modality and to shift their attention between different modalities, as compared with normals (e.g., Ciesielski et al., 1990; Ciesielski, Knight, Prince, Harris, & Handmaker, 1995; Courchesne et al., 1993; Ferstl, Hanewinkel, & Krag, 1994; Sutton, Hakerem, Zubin, & Portnoy, 1961).

Unfortunately, due to several methodological problems, the appropriate interpretation of these prior findings on modality selection is not clear. Alternative accounts which are either entirely nonattentional or involve attention to locations rather than to modalities remain possible. Given the wide interest in modality selection by both normals and clinical populations, it seems important that appropriate methods be developed to index it. With this in mind, the sections below summarize previous studies of selective attention to modalities, in both normal and clinical populations, while highlighting the methodological problems in these studies.

The Apparent Benefits of Knowing Target Modality

Wundt (1893; cited in Sutton & Zubin, 1965) was one of the first to seek empirical support for the claim that subjects can attend to a sensory modality. He reported that people detected stimuli more slowly when target modality was uncertain than when they were sure of the modality in advance. Mowrer, Rayman, and Bliss (1940) similarly found that subjects detected auditory targets more

---

This work was supported by grants from the Medical Research Council (U.K.) and by a Junior Research Fellowship to the first author from St. John's College, Cambridge. Our thanks go to Pierre Jolicouer, Ray Klein, Hal Pashler, Robert Rogers, and Jan Theeuwes for their helpful comments on an earlier version of this manuscript. Correspondence may be addressed to Charles Spence at Department of Experimental Psychology, University of Cambridge, Downing Street, Cambridge CB2 3EB, England (e-mail: cjs1007@cus.cam.ac.uk) or Jon Driver at Department of Psychology, Birkbeck College, University of London, Malet Street, London WC1E 7HX, England (e-mail: j.driver@psyc.bbk.ac.uk).

rapidly when instructed to react only to sounds than when instructed to react to either auditory or visual targets. This benefit occurred even when, in both conditions, only sounds were actually presented following the instructions.

More recently, Boulter (1977) used a trial-by-trial cuing paradigm and found reaction time (RT) benefits for the detection of auditory, visual, and tactile targets when target modality was cued with 100% validity, as opposed to when target modality was uncertain. Comparable benefits for the detection of auditory and visual targets when their modality was expected have been reported in children as young as 4 years of age (Guttentag, 1985, Experiments 1 and 2) and, to varying degrees, in various other normal, schizophrenic, and autistic populations (e.g., Ciesielski et al., 1995; Hohnsbein et al., 1991; A. B. Kristofferson, 1965; M. W. Kristofferson, 1967; Phipps-Yonas, 1984; Simpson, 1972; Waldbaum, Sutton, & Kerr, 1975; though note that some null results have been reported, e.g., Eijkman & Vendrik, 1965; Mulligan & Shaw, 1981; Shiffrin & Grantham, 1974). Unfortunately, it is possible to explain *all* of the positive modality-cuing results in nonattentional terms. The various alternative accounts are illustrated in turn below, by representative studies.

Possible Response Priming Artifacts

Verleger and Cohen (1978) reported improvements from valid modality cuing in both normal and schizophrenic individuals, who had to press one button for auditory targets and another for visual targets. Response latencies were shorter in modality-certain blocks than in target-modality-uncertain blocks. However, this result may reflect response priming rather than a true benefit in perceptual processing for targets in the attended modality. In blocks where target modality was certain, subjects also knew which response to make prior to target presentation (cf. Harvey, 1980). This alone could produce the RT benefit for modality-certain blocks; effectively, a choice RT task has been turned into a simple RT task. This criticism can also be leveled at several other studies that used a modality-discrimination procedure (e.g., Parasuraman, 1985).

Possible Criterion Shifts

The advantage of modality certainty for all the experiments cited so far might merely reflect criterion shifts rather than any form of attentional selection per se (see Mulligan & Shaw, 1981; Shaw, 1984). That is, subjects may just lower their criteria for responding to events in the expected modality rather than becoming more sensitive to them. Results consistent with such an explanation were reported by M. W. Kristofferson (1967). Subjects in her experiment monitored a light and a simultaneous tone, releasing a response key as soon as they detected the offset of either stimulus. Offsets were detected more rapidly in blocks where the modality of offset was certain. On a few catch trials, neither stimulus was terminated, so no response should have been made. In fact, more than twice as many false-alarm responses were made when target modality was certain. This is consistent with a lowered criterion for response in the expected modality rather than a true attentional shift toward it.

Such criterion accounts can be further examined by experiments in which subjects make a speeded *discrimination*, so that both speed and accuracy can be measured. A more risky criterion should result in faster but *less accurate* performance in the expected modality. Posner et al. (1976) reported a study in which subjects made a left/right spatial discrimination regarding the location of auditory and visual targets. In "expect-auditory" blocks, the majority (80%) of the targets were auditory and the remainder were visual. Performance for these blocks was compared with blocks that had either equal numbers of auditory and visual targets or a majority of visual targets ("expect vision"). Responses were faster *and more accurate* for auditory targets in the expect-auditory blocks than in the expect-vision blocks (and vice versa for visual targets). These complementary RT and accuracy effects make criterion accounts implausible. Moreover, response priming cannot account for these findings either, because the appropriate response for each target could not be anticipated in any condition. Similar effects were reported by Klein (1977, Experiment 1), who used the same left/right blocked discrimination task, and have also been found in a range of further discrimination tasks when the likely modality is blocked (Eijkman & Vendrik, 1965; Harvey, 1980, Experiment 2; Hohnsbein et al., 1991; A. B. Kristofferson, 1965, Experiment 4; Massaro & Kahn, 1973; Massaro & Warner, 1977).

However, due to an unintended confound between expectancy-based factors (henceforth referred to as *endogenous*) and stimulus-driven factors (termed *exogenous*), there is a further problem in interpreting all of these studies. The distinction between exogenous and endogenous attention has turned out to be critical in research on spatial covert attention (Jonides, 1981; Klein, Kingstone, & Pontefract, 1992; Rafal, Calabresi, Brennan, & Sciolto, 1989; Spence & Driver, 1994; 1996, 1997). We suspect that it will be equally important in the analysis of attention to modalities, as described below.

Expectancy Effects or Stimulus-Driven Modality-Shifting Effects?

The most common interpretation for the blocked-cuing technique just described, where one modality is consistently more likely than another over a whole block of trials, has been that improvements in performance for the more common (and thus expected) modality are due to a voluntary shift of endogenous attention to that modality. However, this overlooks potential intertrial effects of an exogenous nature. For instance, regardless of any expectancies, there may be some cost in responding to targets when their modality changes successively—or some benefit in responding to a repeated sequence of identical stimuli. Such exogenous stimulus-repetition factors are perfectly confounded with the expectancy manipulation in blocked designs. For instance, as visual targets become more likely overall in a block, the proportion of visual–visual sequences for successive targets versus auditory–visual sequences must also increase.

Numerous findings demonstrate a robust performance cost, or modality-shifting effect (MSE), whenever target modality changes between successive trials (e.g., Dinnerstein & Zlotogura, 1968; Ferstl et al., 1994; Hannes, Sutton, & Zubin, 1968; Kristofferson, 1965; Mowrer et al., 1940; Robin & Rizzo, 1989, 1992; Spence, Driver, & Rogers, 1997; see also Pashler & Baylis, 1991, for a discussion of the numerous repetition effects found in other contexts). That is, subjects respond more rapidly to a target when the preceding trial had a target in the same modality (ipsimodal trial) than when it was in a different modality (cross-modal trial). The MSE can occur even when stimulus and response uncertainty are removed (Spring, 1980; Waldbaum et al., 1975), and it is primarily influenced by the sequence of imperative target stimuli (Rist & Cohen, 1987; Rist & Thurm, 1984; Spring, 1980) and is little influenced by interspersed nontarget stimuli.

The nature of the confound in blocked designs, between MSEs and endogenous attentional factors, may become clearer if we take the Posner et al. (1976) study that was described earlier as a concrete example. In their experiment, 80% of targets in the expect-auditory blocks were auditory. Most of these auditory targets would therefore occur on ipsimodal trials (i.e., the auditory target was more likely to have been preceded by another auditory target than by a visual target). In contrast, the majority of auditory targets in the expect-vision blocks would be on cross-modal trials (i.e., the auditory target was more likely to have been preceded by a visual target than by another auditory target). It is therefore possible that RTs to auditory targets were elevated in the expect-vision blocks, as compared with expect-auditory blocks, solely due to the cost associated with an exogenous, stimulus-driven MSE rather than because of any endogenous shift of attention to the expected modality.

This confound between the MSE and endogenous factors extends to all the other blocked cuing studies we have cited so far (e.g., Hohnsbein et al., 1991; Klein, 1977; Kristofferson, 1965). The present article is not concerned with the exact mechanisms that produce the widely observed MSE or with whether these are attentional in nature (for experiments on that issue, see Spence et al., 1997). For present purposes, the important point is that, by definition, the MSE is a purely stimulus-driven effect, depending only on whether successive stimuli have the same modality, regardless of any expectations. It is thus different in kind from the deliberate direction of endogenous attention toward an expected modality that has usually been invoked to explain modality-certainty effects in blocked designs.

In one previous study, Dinnerstein and Zlotogura (1968) did seek to overcome the confound between exogenous MSEs and endogenous expectancy effects when using a blocked modality-cuing paradigm. When comparing detection latencies for blocks where all targets were of the same modality versus blocks where target modality was uncertain, their technique was to analyze cross-modal and ipsimodal trials separately. Performance was faster on *ipsimodal* trials in the modality-certain blocks than on *ipsimodal* trials in the modality-uncertain blocks (apparently demonstrating the effects of endogenous attention to a sensory modality). In turn, performance was faster on these ipsimodal trials than on *crossmodal* trials in the modality-uncertain block (demonstrating a separable MSE). However, Dinnerstein and Zlotogura unfortunately used *detection* latencies as their critical performance measure, and so the criterion account discussed earlier cannot be ruled out for their data.

Trial-by-trial cuing procedures (e.g., Boulter, 1977; Posner, Nissen, & Ogden, 1978) provide an alternative means to Dinnerstein and Zlotogura's (1968) analysis for separating modality-expectancy effects from exogenous influences such as the MSE. With this method, the likely modality for the next target can be changed unpredictably from trial to trial, being signaled by a cuing event. As a result, cross-modal and ipsimodal trials (with respect to the target modality of the preceding trial) can occur equally often for targets in the expected and unexpected modalities. Hence, any advantage found for targets in the expected-modality trials cannot be due to an MSE. Such advantages have indeed been reported by some previous studies (e.g., Boulter, 1977; Posner et al., 1978). However, due to yet another type of confound, which applies to the vast majority of prior studies of modality selection, the interpretation of such results still remains problematic. This confound arises because targets from distinct modalities have typically been presented from different positions.

Modality-Cuing or Spatial-Cuing Effects?

In the prototypical modality-cuing experiment, auditory targets are presented over headphones and visual targets are presented on a monitor placed in front of the subject. For instance, in the "expect-vision" trials of the Posner et al. (1976) study, 80% of the targets were presented from the screen in front of the subject, whereas in the "expect-auditory" blocks, the majority of targets were presented over headphones at the head. Accordingly, subjects may not have been using their advance knowledge to direct attention to a particular *modality* per se, but rather to direct their attention to one location or another (e.g., in front and below for the visual events, but closer to the head for the auditory events). Responses might then have been slower for auditory targets on "expect-vision" trials than on "expect-audition" trials simply because attention was directed to the wrong location, and *not* because it was directed to the wrong modality. Furthermore, any such orienting of attention to the likely target location could even have occurred *overtly*, as eye movements have not been monitored, or even fixation instructions described, in the vast majority of previous modality-cuing experiments.

A spatial-cuing interpretation for previous modality-cuing results is made all the more plausible when one considers the many studies showing that people invariably use spatially informative cues to shift their endogenous attention to the expected target location (see Klein et al., 1992). This applies both in vision and in hearing (Spence & Driver, 1994; 1996, 1997). The possible relevance of such spatial selection for previous studies purporting to measure modality selection is perhaps best illustrated by example. Boulter (1977) presented sounds over headphones and lights from a more distant position. He compared conditions where target modality (and thus, inadvertently, target location) was 100% certain, with conditions where target modality (and thus target location) was unknown. Performance was better on modality-certain trials. However, this may have arisen simply because it is more efficient to focus endogenous spatial attention on a single location (as in the modality-certain conditions) than to divide spatial attention across different locations (as required in the modality-uncertain condition). Indeed, Driver and Spence (1994; Spence & Driver, 1996) have recently documented that attending to different locations in hearing and vision is less efficient than concentrating on a common location across the modalities.

Such purely spatial reinterpretations of modality-certainty effects are possible for every modality-cuing experiment in which auditory and visual targets were presented from different positions. In fact, this applies for the vast majority of previous studies on modality selection (e.g., Dinnerstein & Zlotogura, 1968; Eijkman & Vendrik, 1965; Guttentag, 1985; Hafter & Bonnel, 1995; Harvey, 1980; Hohnsbein et al., 1991; Kristofferson, 1965; LaBerge, 1973; LaBerge, Van Gelder, & Yellott, 1970; Mowrer et al., 1940; Parasuraman, 1985; Phipps-Yonas, 1984; Shiffrin & Grantham, 1974; Verleger & Cohen, 1978). The confound of modality with location also applies for most studies that have implemented event-related potential (ERP) measures in addition to purely behavioral measures of attention to a modality (e.g., Alho, Woods, & Algazi, 1994; Alho, Woods, Algazi, & Näätänen, 1992; Ciesielski et al., 1990, 1995; Hackley, Woldorff, & Hillyard, 1990; Münte, Blum, & Heinze, 1993; Woods, Alho, & Algazi, 1992).

In summary of all the preceding sections, many studies of modality cuing for auditory and visual targets have found performance advantages when stimuli are presented in an expected modality. Such advantages have usually been attributed to endogenous covert shifts of attention to the expected modality. However, these prior findings can all be attributed instead to response priming, criterion shifts, stimulus-driven MSEs, or inadvertent spatial-cuing effects. To our knowledge, only one published study might be argued to circumvent all of these potential problems. This is a study reported by Posner et al. (1978, Experiment 4), which concerned attention to *touch* versus vision.

Posner et al. (1978) required subjects to make a speeded discrimination regarding the intensity (high vs. low) of light flashes or vibrotactile stimuli. The use of such a discrimination task renders both response-priming and criterion accounts for any modality-expectancy effect implausible. Tactile stimuli were presented via either of two buzzers situated under the index fingers of the left and right hands; visual targets were presented via LEDs on the left or right directly next to these buzzers (thus minimizing any confound of modality with position). Visual and tactile targets were presented in equal proportions and in a random order (thus minimizing any confounds of modality expectancy with stimulus sequence, and hence avoiding any contamination by the MSE). The results were that visual cues that predicted the likely target modality for the current trial produced RT benefits when valid and costs when invalid relative to a neutral cue. These RT effects were matched by similar trends in the error data, ruling out criterion-shift accounts.

The most plausible account for these results is that people can endogenously direct their covert attention to vision rather than to touch, or vice versa. Some caution should be exercised, however, before extrapolating from Posner et al.'s (1978) findings concerning touch and vision to our case of attention for the auditory versus visual modalities. Several recent studies have questioned the similarity of attentional effects reported across different sensory modalities. For example, spatial cues predicting the likely target location under conditions of modality uncertainty are effective when the target is either *auditory* or visual (see Spence & Driver, 1996) but apparently not when the target is *tactile* or visual (Posner et al., 1978). Furthermore, asymmetrical links between exogenous spatial orienting across the auditory and visual modalities have recently been reported (Spence & Driver, 1997). These findings demonstrate that attentional phenomena observed for one pairing of sensory modalities need not extend to a different combination of modalities.

Given these concerns, and our own interests in the ability to allocate attention specifically to the *auditory* or visual modalities, our first study followed the general logic of the Posner et al. (1978) experiment (i.e., cuing the likely target modality on a trial-by-trial basis while leaving target location equally uncertain in each modality), but now presented visual and *auditory* targets from comparable locations. On each trial, a visual cue indicated that the subsequent target was more likely to be presented in one modality or the other, or that the two modalities were equally likely, but this cue gave no indication as to which location the target would be presented from. Subjects were required to make a speeded detection response, irrespective of target modality. With a view to examining any criterion shifts, catch trials in which no target stimulus was presented (and where responses had to be withheld) were also included unpredictably.

If people can allocate their covert attention to the auditory versus visual modalities, then RTs to auditory targets should be faster following a valid expect-auditory cue than following an invalid expect-vision cue, whereas visual detection should be faster after the expect-vision cue. If subjects simply lower their criteria for responding to signals in the cued modality, then this should result in an increased rate of erroneous responses (false alarms) on catch trials following a modality cue than on those following a neutral cue, as previously found by Kristofferson (1967). We reasoned that if subjects were specifically instructed to *avoid* lowering their criterion for responding to the cued modality, then they might show an attentional facilitation of RTs, without any concomitant increase in false alarms, assuming selective attention to audition or vision is indeed possible.

EXPERIMENT 1

This study investigated whether subjects could use advance information about likely target modality in order to direct their attention endogenously to audition or vision on a trial-by-trial basis. Targets were randomly presented from one of four target locations situated 18.7° above or below the midline and 52.7° to either side of fixation (see Figure 1 for a schematic view of the experimental setup seen from a raised position behind the subject's head). Targets were presented equally often in each modality and from each of the four locations. A central visual cue informed the subjects on each trial to direct their attention to audition, or to vision, or to both modalities in the neutral divided-attention condition. The subjects were required to make a simple detection response on trials when a target was presented, while making no response on catch trials where no target was presented.

Method

Subjects. Ten subjects were recruited (8 men and 2 women) through advertisements; all were naive as to the purpose of the experiment. Their mean age was 25 years, with a range of 21–41 years, and all except 1 was right-handed by self-report. All reported normal hearing and normal or corrected-to-normal vision.

Apparatus and Materials. All the studies were conducted in a darkened soundproof booth (178 × 122 × 91 cm) with a background luminance of 0.12 cd/m^2. The subject sat at a table and faced straight ahead, with his/her head resting in an adjustable chinrest. The cue and fixation lights were located 45 cm in front, in a row at eye level. The fixation light was an amber LED at the center, and the cue lights were arranged on the horizontal plane, as shown in Figure 1, covering a distance of 5 cm between the most eccentric cue lights. The expect-vision cue consisted of the illumination of the two red LEDs situated at 0.9° from fixation. The expect-audition cue consisted of the illumination of the two green LEDs situated 3.0° from fixation, and the illumination of both the red and the green cue lights served as a neutral cue to signal divided attention.

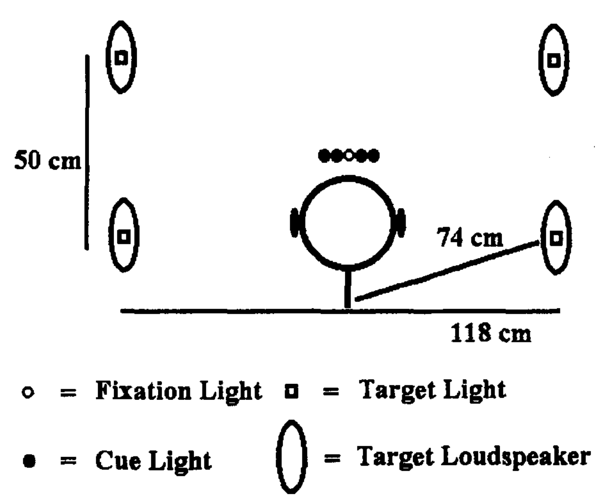

Figure 1. Schematic view of the positions of the fixation, cue, and target lights, plus target loudspeakers in Experiment 1, as seen from a raised position behind the subject's central cartooned head.

The auditory targets were presented from one of four box-mounted oval loudspeaker cones (12.7 × 7.6 cm, 8Ω, 20 W, Radio Spares Part No. RS 245-304). Each auditory target consisted of five 20-msec white-noise bursts presented at 75 dB(A), as measured from the subject's ear position, each burst separated by a 10-msec silent gap. These sounds were chosen to be highly localizable (see Spence & Driver, 1994; 1996, 1997). A bright red LED (luminance of 64.3 cd/m^2) was placed directly in the front of the middle of each of the four loudspeaker cones. The visual targets consisted of the uninterrupted 150-msec illumination of one of these LEDs. The subjects were required to press a button situated on the table directly in front of them as soon as they detected a target, irrespective of its modality or location. RTs were measured in milliseconds from target onset, using an 82C54 interval-timer chip on one of the input-output cards (Blue Chip Technology parts DCM-16 and DOP-24), which interfaced to the loudspeaker cones, LEDs, and response buttons.

Design. The two within-subjects factors were target modality (auditory or visual) and cue validity (valid, neutral, or invalid). There were 60 practice trials, followed by six test blocks of 162 trials each. In each experimental block there were 104 (64%) valid trials, where the target modality was correctly predicted by the cue, 26 (16%) neutral trials, 26 (16%) invalid trials, and 6 (4%) catch trials (2 after an expect-vision cue, 2 after a neutral divided-attention cue, and 2 after an expect-audition cue). An equal number of auditory and visual targets were presented from each of the four possible target locations within each block of trials. The cue validity was the same for both modalities, vision and audition were cued equally often, and the various conditions appeared in random order.

Procedure. The fixation light was illuminated at the beginning of each trial. The subjects were instructed to foveate its location throughout each trial. In any case, auditory and visual targets could appear only at the same four locations on the corners of a large imaginary rectangle centered at fixation, and thus particular eye movements could not favor either modality. After 300 msec, the fixation light was turned off and the central modality cue was presented for a period that varied randomly between 600 and 900 msec. The target was presented as this cue was extinguished. The subjects were required to press the response button on trials in which they detected a target and to refrain from responding on the catch trials. They were told to respond as rapidly and as accurately as possible. The trial was terminated after 1,000 msec if no response had been made. The subject was given feedback in the form of the fixation light flickering for 270 msec if a response was erroneous (either failing to make a response when a target occurred or responding when no target had been presented). Otherwise, all lights were extinguished on response and remained so for 500 msec before the next trial was initiated. Subjects were told about the cue validities at the beginning of the experiment, and were requested at the start of every block to attend to the modality indicated by the cue as most likely for the next target.

Results

The first block of trials was treated as practice and was therefore not analyzed. Trials on which an incorrect response occurred and trials immediately succeeding an incorrect response were also discarded from the RT analysis. In addition, trials on which the RT was below 50 msec or over 1,000 msec were removed. These latency criteria removed less than 2% of trials. The intersubject mean RTs (after these exclusions), together with the mean "costs plus benefits" (i.e., the difference between RTs for invalid and valid trials), are shown in Table 1. Mean, rather than median, RTs were computed for each subject because the different cue conditions had different probabilities of occurrence (see Miller, 1988), with valid trials being more likely. In the analyses reported in the main text for every experiment in this article, data were pooled across the factor of target position, which never produced any critical interaction with the factors of primary interest. However, at the suggestion of a reviewer (Ray Klein), the Appendix also presents further analyses, which include the target-position factor, for completeness.

The RT data were analyzed using a within-subjects analysis of variance (ANOVA), with the factors of target modality (auditory or visual) and cue validity (valid, invalid, or neutral). There was a highly significant main effect of modality [$F(1,9) = 408.4, p < .0001$], with subjects responding more rapidly to auditory targets (M = 281 msec) than to visual targets (M = 344 msec). The effect of validity was also significant [$F(2,18) = 6.3, p = .008$], with subjects responding more rapidly on validly cued trials than on neutrally cued trials and with slowest responses on invalid trials. The interaction between target modality and validity was close to significance [$F(2,18) = 2.9, p = .08$]. Pairwise comparisons (t tests) of these data showed that the neutrally cued trials were significantly faster than invalidly cued trials for both auditory (mean of 18 msec, $p < .01$) and visual target trials (mean of 10 msec, $p < .05$). However, validly cued trials were significantly faster than neutrally cued trials only for visual targets (mean of 14 msec, $p < .01$) and not for auditory targets (mean of −2 msec, n.s.). Analysis of the false-alarm data revealed that subjects made slightly fewer errors on catch trials where vision was the cued modality (mean of 4.7%) than on either auditory-cued or neutral-cued trials (mean of 5.3% for both). A one-way ANOVA [type of cue (3)] revealed that this trend was not significant [$F(2,18) = .1$, n.s.].

Discussion

The results of Experiment 1 show that symbolic cues which predict the likely target modality on a trial-by-trial basis can influence the detection of targets presented in the expected versus the unexpected modality, with better performance in the former case. This result extends the numerous previous modality-cuing studies that have used a detection response (e.g., Guttentag, 1985, Experiments 1 and 2; Hohnsbein et al., 1991; A. B. Kristofferson, 1965; M. W. Kristofferson, 1967; Mowrer et al., 1940; Phipps-Yonas, 1984; Simpson, 1972; Waldbaum et al., 1975). In contrast to the vast majority of such prior studies, the modality cues used in this experiment provided no *spatial* information with regard to the likely target location, as auditory and visual targets appeared in the same set of widely dispersed possible locations. Therefore, these results cannot be attributed to any inadvertent form of spatial cuing. Nor can they be attributed to response priming, because the same response was used regardless of target modality, or to any inadvertent confound of modality expectancy with the MSE, because, target modality was equally likely to be the same or different from that of the target on the previous trial for all conditions.

Table 1
Mean Reaction Times (in Milliseconds), Their Standard Deviations, and Mean Costs Plus Benefits for Auditory and Visual Targets in the Detection Task of Experiment 1

	Cue Validity						
	Valid		Neutral		Invalid		
Target Modality	*M*	*SD*	*M*	*SD*	*M*	*SD*	Costs Plus Benefits
Auditory	276	64	274	57	292	64	16*
Visual	331	65	345	63	355	63	24*

Note—By t test pairwise comparison: *$p < .01$.

Analysis of the error rates from the catch trials revealed no tendency for subjects to make more erroneous responses (false alarms) on trials where a modality cue was presented than on neutral-cue trials. This null effect on overall false alarms suggests that subjects were not lowering their criteria for responding to stimuli in the cued modality (e.g., as compared with the neutral condition). However, it is possible that they may have simultaneously lowered their criteria in the expected modality and raised them for the unexpected modality, as compared with the neutral condition.[1] Accordingly, to rule out the possible criterion-shift account, our subsequent experiment used a discrimination response. Subjects were now required to make a discrimination response regarding the intensity (loud vs. quiet) of auditory targets and the color (red vs. yellow) of visual targets. Any trials on which an erroneous response was made here can presumably be identified with the presented target modality (e.g., a yellow response to a red target will unambiguously count as a visual rather than auditory error). We predicted that subjects should be both faster and/or more accurate when responding to targets presented in the expected modality, which was again cued on a trial-by-trial basis.

EXPERIMENT 2

Method

Subjects. Twelve new subjects (7 men and 5 women) were recruited as in Experiment 1; all of them were naive as to the purpose of the experiment. Their mean age was 23 years, with a range of 19–30 years, and all were right-handed by self-report.

Apparatus and Materials. The apparatus and materials were as in the previous experiment, with the following exceptions. The loud target sound was presented at 75 dB(A), and the quiet target, at 55 dB(A). An additional yellow turbo LED (luminance of 41.4 cd/m^2) was placed to the immediate right of each of the four red target LEDs used in Experiment 1. The subjects were required to press one button in response to the loud sound or the yellow light and another button, with the other hand, in response to the quiet sound or the red light. The buttons were located, one in front of the other, on the table directly in front of the subject. Each response was equally likely to be appropriate following each modality cue.

Design. The two within-subjects factors were target modality (auditory or visual) and cue validity (valid, neutral, or invalid with regard to target modality) as before. No catch trials were presented in this experiment. For all subjects, 60% of all trials had valid cues, 20% had neutral, and 20%, invalid. There were 70 practice trials, followed by six test blocks of 160 trials each. The four different possible targets (red light, yellow light, loud sound, or quiet sound) were presented equally often from each of the four possible target locations within each block of trials. The cue validity was the same for both modalities, and the various conditions appeared in random order.

Procedure. The procedure was as for Experiment 1, with the following exceptions. The subjects were now required to press the key further away from them for a loud auditory target or a yellow light target and the nearer key for a quiet sound or a red light and to respond as rapidly and accurately as possible. They were allowed 2,000 msec in which to respond before the trial was terminated. If no response was made within this time or if an incorrect response was made, feedback was given by a flickering fixation light, as before.

Results

Trials on which the RT was below 50 msec or over 1,500 msec were discarded from the analysis. This removed less than 5% of the trials. The intersubject mean RTs (after these exclusions), together with the mean "costs plus benefits" (i.e., invalid minus valid differences) and the corresponding error rates for each condition across all trials are shown in Table 2. The RT data were analyzed using a within-subjects ANOVA with the factors of target modality (auditory or visual) and cue validity (valid, invalid, or neutral). There was a main effect of modality [$F(1,11) = 16.0, p = .002$], with subjects responding more rapidly to auditory targets than to visual targets. There was also a significant effect of validity [$F(2,22) = 7.4, p = .004$], with subjects responding more rapidly on validly cued trials than on neutrally cued trials and with slowest responses on invalid trials. There was no interaction between target modality and validity [$F(2,22) = 1.3$, n.s.]. Pairwise comparisons (t tests) of these data showed that neutrally cued trials gave significantly faster responses than invalidly cued trials for auditory target trials (mean of 27 msec, $p < .01$), but not for visual targets (mean of 13 msec, n.s.). Validly cued trials were significantly faster than neutrally cued trials for visual targets (mean of 19 msec, $p < .05$) but not for auditory targets (mean of 1 msec, n.s.). An analogous ANOVA on the error data revealed no significant effects or interactions ($F < 1$ for all terms).

Discussion

The results of the second study show once again that response latencies can be influenced when subjects are given advance information concerning the likely target modality. For both auditory and visual targets, discrimination was more rapid on valid trials than on invalid trials, with intermediate performance on neutral trials in the visual modality. The difference between valid and invalid trials was the only comparison to reach significance in both modalities. It is possible that the size of the overall validity effect (costs plus benefits) may have been too small to permit significant differences to emerge between the neutral conditions and those on which either a valid or invalid cue was presented, given the power of the experiment.

Criterion shifts do not offer a natural explanation for these cuing effects, as discrimination rather than detection was required. Less cautious responding for targets in the expected modality might have produced an RT advantage, but this alone should have been offset by an increase in errors for targets in the cued modality, which we did not reliably find. The size of the overall costs plus benefits for valid versus invalid modality cues was similar in the two modalities (see Table 2).

However, one methodological concern with any interpretation of Experiment 2 in terms of endogenous attention to the cued modality remains. One of two quite different tasks (color vs. loudness discrimination) was required, depending on the modality of the target presented. It is possible that subjects may have used the modality cue simply in order to prepare for one or the other of these different tasks (cf. Allport, Styles, & Hseih, 1994; Rogers & Monsell, 1995) rather than in order to attend to a particular modality. According to this interpretation, subjects may use the attend-auditory cue as an instruction to prepare for intensity discrimination and the attend-vision cue to prepare for color discrimination. If preparation for a particular task reduces response latencies, the validity effects described in Experiment 2 might be attributed entirely to endogenous *task* preparation rather than to the beneficial effects of directing attention to one sensory modality versus another.

Several recent studies have shown that a cost is incurred on trials where the task is changed from that of the previous trial, as compared to performance on trials with the task repeated (e.g., Allport et al., 1994; Rogers & Monsell, 1995). This task-switching cost occurs across a wide variety of task combinations. More importantly for our purposes, it is reduced (although not completely eliminated) when subjects are informed in advance that a task switch is about to occur. Rogers and Monsell (1995) have suggested that this reduction with advance information

Table 2
Mean Reaction Times (in Milliseconds), Their Standard Deviations, Mean Costs Plus Benefits, and Percentages of Errors for Auditory and Visual Targets in the Intensity/Color Discrimination Task in Experiment 2

	Cue Validity									
Target	Valid			Neutral			Invalid			Costs Plus
Modality	*M*	*SD*	Errors	*M*	*SD*	Errors	*M*	*SD*	Errors	Benefits
Auditory	582	148	6.3%	583	137	5.8%	610	138	6.1%	28*
Visual	652	147	5.9%	671	143	6.0%	684	131	5.1%	32*

Note—By t test pairwise comparison: $^*p < .01$.

is caused by the endogenous reconfiguration of task set (see also Dixon & Just, 1986). Since task-preparation effects can arise even when all possible tasks in the experimental situation arise within the same sensory modality, it could be suggested that our present cuing effects have absolutely nothing to do with preparation for one modality versus another, but simply reflect preparation for one task versus another.

One approach to this problem is to use a discrimination task that is the same in the two modalities (or at least is as nearly the same as possible, given the absolute necessity of presenting stimuli in different modalities). One task which might fit this criterion is the spatial discrimination task (left vs. right) previously used by several other researchers for studying modality selection (e.g., Klein, 1977; Posner et al., 1976; Simpson, 1972). One cannot be certain a priori that this discrimination of azimuth will constitute exactly the same task for targets in the two modalities. Indeed, definitions of exactly what would constitute a single common "task" are extremely scarce (see Rogers & Monsell, 1995, for a discussion of this point). However, it does at least seem certain that the stimulus–response mapping required for the two modalities would be more similar in a spatial discrimination task, where any auditory or visual target presented on the left is paired with a left response and right stimuli are always paired with right responses, than it would be for our previous tasks (Experiment 2), where a loud auditory target and a yellow visual target had to be mapped to the same response, while quiet sounds were mapped with red lights.

Furthermore, evidence reported by Auerbach and Sperling (1974) suggests that auditory and visual direction may in fact be represented as a single common dimension. Subjects in their study were required to judge whether two sequentially presented stimuli (auditory or visual) came from the same or different positions. Judgments of relative position for the two targets were no less variable if both targets were of the same modality than if one was auditory and the other visual. Auerbach and Sperling argued that if the representations of auditory and visual azimuths had been coded in *separate* modality-specific representations, then there should have been a greater variability in responding when the comparison stimuli were of different modalities than when both targets were of the same modality and therefore could be judged on the basis of the same representation.

Auerbach and Sperling (1974) concluded that the locations of auditory and visual stimuli are coded in a common representation. Taking this point, together with our observations about equivalent stimulus–response mappings within a compatible localization task, auditory and visual spatial discrimination may fit our requirement for a pair of tasks where advance information about the probable target modality is unlikely to provide crucial information for a complex reconfiguration of task set. We return to this issue in the General Discussion.

EXPERIMENT 3

In Experiment 3, we attempted to replicate the modality-cuing effects reported in our previous studies, but now using just one common spatial discrimination task for targets in both modalities. The design of this study was very similar to that of Experiment 2, with the exception that subjects were now required to discriminate either the azimuth of targets in both modalities (left vs. right, irrespective of the elevation of the target) or their elevation (up vs. down, irrespective of the side of target presentation). The azimuth task is similar to the one used by several other researchers to investigate modality selection (Klein, 1977; Posner et al., 1976; Simpson, 1972), except that our stimuli for it could also vary in elevation.

As in our previous experiments, subjects were cued at the beginning of each trial as to the likely modality of the target, although cue validity was now increased slightly due to the removal of neutral-cue trials, in order to increase power and simplify the design (i.e., we now measured just costs plus benefits from modality cuing). The cue correctly predicted the modality of the target on 83.3% of the trials and was invalid on the remaining 16.7% of trials. Subjects performed the azimuth discrimination task during one half of the experiment, and the elevation task during the remainder, with the order of presentation for the tasks counterbalanced across subjects. Our use of both azimuth and elevation tasks was dictated by an ongoing series of other experiments, tangential to the main issues here. The critical point for our present purposes is that if we can assume that the equivalent localization tasks for auditory and visual targets represent variations of the same basic task across sensory modalities, rather than entirely distinct tasks, then any validity effects may be unambiguously attributed to endogenous shifts of attention to the likely target modality rather than to endogenous task preparation.

Method

Subjects. Ten new subjects (4 men and 6 women) were recruited to take part in this experiment; all were right-handed by self-report. Their mean age was 26 years, with a range of 18–42 years.

Apparatus and Materials. The apparatus and materials were as in Experiment 2, with the following exceptions. The subjects performed the elevation task using the same buttons as in Experiment 2 (where they had been used for the color and intensity-discrimination tasks), now pressing the key further away from them for a target from either of the upper positions (regardless of side and modality) and the nearer key for a target from either of the lower target positions. Two additional response buttons were used during the azimuth discrimination task, which was run in separate blocks. One of these additional buttons was located to the left of the up/down buttons and the other, to the right. The subjects pressed the left button for a target from either of the left loudspeaker cones or adjacent LEDs (now regardless of elevation as well as modality) and the right button for targets presented from either of the loudspeaker cones or LEDs situated to the right. Thus, in all cases, the position of the key was compatible with the localization response required.

Design. The subjects were given up to 100 practice trials, followed by four blocks of 144 experimental trials for each task. Five subjects started with four blocks of the elevation-discrimination task; the other 5 subjects started with the azimuth discrimination. There were 120 (83.3%) valid trials and 24 (16.7%) invalid trials within each of the experimental blocks. The three within-subjects factors were task discrimination (elevation or azimuth), target modality (auditory or visual), and validity (valid or invalid).

Results

The usual latency criteria removed 1.5% of trials from the azimuth discrimination task and 4.4% of trials from the elevation task. The mean RTs are shown in Table 3, along with corresponding error rates. A three-way within-subjects ANOVA was conducted on the RT data, with the factors of task discrimination (elevation or azimuth), target modality (auditory or visual), and cue validity (valid or invalid). There was a highly significant main effect of task $[F(1,9) = 97.7, p < .0001]$, with subjects responding more rapidly when making an azimuth discrimination than when making an elevation judgment. The factors of task and modality interacted $[F(1,9) = 19.6, p < .002]$, revealing that subjects responded more rapidly to auditory targets than to visual targets in the azimuth task, but more rapidly to visual targets in the elevation task, consistent with the known localization limits in these modalities. Pairwise comparisons (t tests) revealed that the only significant difference between the modalities was for the elevation-discrimination task (mean difference between auditory and visual RTs = 49 msec, $p < .01$).

The effect of cue validity was significant $[F(1,9) = 20.4, p < .002]$, with subjects responding more rapidly on valid trials than on invalid trials. None of the other effects or interactions were significant [for modality, $F(1,9) = 1.8, p = .21$; for task × modality × validity, $F(1,9) = 1.7, p = .23$; for all other interactions, $F < 1$]. Pairwise comparisons (t tests) confirmed that the modality-cuing effect was significant for both tasks in both modalities (see mean costs plus benefits in Table 3). An equivalent ANOVA on the error data revealed a significant main effect of task $[F(1,9) = 6.3, p = .03]$ caused by subjects' making more errors on the elevation task than on the azimuth task. None of the other effects or interactions were significant [for validity, $F(1,9) = 3.3, p = .10$; for modality, $F(1,9) = 3.6, p = .09$; and for task × validity, $F(1,9) = 2.0, p = .19$; for all other terms, $F < 1$]. However, note that the numerical trend in errors was for poorer performance on invalid trials, in agreement with the RT data.

Discussion

The results of Experiment 3 demonstrate that subjects could discriminate both the elevation and azimuth of auditory and visual targets more rapidly when correctly cued as to the likely target modality. This advantage for targets in the expected modality was also present numerically in the error-rate data. To reduce the possibility that the modality-expectancy effects merely reflected task cuing, we had used a spatial discrimination task in which the stimulus-response mapping was highly compatible for targets in both modalities. Such a task-cuing explanation seems intuitively more plausible when two obviously different tasks are arbitrarily paired together, as with, for example, the auditory intensity and visual color discrimination tasks paired in Experiment 2. It seems less plausible for the similar and compatible tasks used across the two modalities here.

As discussed earlier, the modality-cuing benefits reported in most previous studies might be explained solely in terms of *spatial* orienting effects because targets from different modalities appeared in quite separate positions. We have now successfully demonstrated modality-cuing effects when this spatial confound is removed. However, this leads to a further question: Was the inadvertent spatial-cuing information inherent in previous studies actually used by the subjects, given that our own results show that modality cuing alone can affect performance? It is possible that, under conditions where a cue informs subjects both of the likely modality of the target and of its likely position, the subjects may use only one form of expectancy in directing their attention. The subjects might focus their attention entirely upon the expected modality, ignoring information that is also potentially available regarding the likely target location. If so, the spatial confounds discussed earlier in previous research would become relatively insignificant. Alternatively, they might use the spatial information that was inadvertently given by modality cues in prior studies as well as (or instead of) the modality information.

Table 3
Mean Reaction Times (in Milliseconds), Their Standard Deviations, Mean Costs Plus Benefits, and Percentages of Errors for Auditory and Visual Targets in the Azimuth and Elevation Discrimination Tasks in Experiment 3

Target	Cue Validity						Costs Plus
	Valid			Invalid			
Modality	*M*	*SD*	Errors	*M*	*SD*	Errors	Benefits
			Elevation Discrimination				
Auditory	548	100	8.0%	587	117	9.4%	39*
Visual	507	79	1.9%	530	93	3.1%	23†
			Azimuth Discrimination				
Auditory	374	64	0.8%	397	65	1.0%	23†
Visual	397	55	1.4%	426	72	1.5%	29*

Note—By *t* test pairwise comparison: *$p < .05$, †$p < .05$.

Thus, it still remains unclear whether the many previous studies described in our introduction actually measured attention to a modality, as they claimed, or merely attention to the locations that were inadvertently confounded with modality; or perhaps they measured some unknown combination of these two processes. This difficulty in interpretation applies for numerous prior studies with normal populations (e.g., Dinnerstein & Zlotogura, 1968; Eijkman & Vendrik, 1965; Guttentag, 1985; Hafter & Bonnel, 1995; Harvey, 1980; Hohnsbein et al., 1991; Kristofferson, 1965; LaBerge, 1973; LaBerge et al., 1970; Mowrer et al., 1940; Parasuraman, 1985; Phipps-Yonas, 1984; Shiffrin & Grantham, 1974; Verleger & Cohen, 1978) and also with schizophrenic populations (e.g., Ferstl et al., 1994; Sutton et al., 1961) and autistic populations (e.g., Ciesielski et al., 1990, 1995; Courchesne et al., 1993), as considered further in the General Discussion.

Our final study sought to test whether people could use advance information about *both* likely target modality *and* likely target position to direct their covert attention. Our purpose was to examine whether future studies of modality selection should take potential spatial confounds seriously. In Experiment 4, we used an azimuth discrimination paradigm similar to that in Experiment 3, with the exception that targets could now be presented from only a single position on either side of the subject's midline, because no elevation task was used (i.e., there was no longer any variation in vertical location). In some blocks of trials, auditory targets were presented monaurally over headphones and visual targets were presented from in front of the subject, as in the previous studies reported by Klein (1977) and Posner et al. (1978), among many others. Since all sounds came from the headphones but all lights came from LEDs in front of the subject, cues to the likely target modality now also gave information about likely target position (i.e., in front and below in the case of the lights, but at the head in the case of the sounds). Thus, this new arrangement deliberately reintroduced the confound between modality and position that had been inadvertently present in most previous studies of modality selection, as discussed earlier.

For other blocks of trials in our final study, auditory targets were presented from external loudspeaker cones placed directly behind the target LEDs, as in our preceding experiments in this study. If modality cuing completely overrides spatial cuing, then there should be no difference between the size of the validity effects for modalities seen under these two conditions. However, if inadvertent spatial cuing also occurs when modality cues are given and targets from distinct modalities appear in different locations, then we should see larger validity effects under the headphone-presentation conditions (where both modality and spatial-cuing information is available) than under the external loudspeaker condition (where only modality-cuing information is present).

EXPERIMENT 4

Method

Subjects. Fourteen new subjects (7 men and 7 women) were recruited to take part in this experiment; all were right-handed by self-report. Their mean age was 27 years, with a range of 20–46 years.

Apparatus and Materials. These were as in Experiment 3, with the following exceptions. There were now only two rather than four possible positions for auditory and visual targets, with one on either side of fixation. In some conditions (no spatial cuing), auditory and visual targets were presented from the same two possible external locations, with auditory targets presented from one of two loudspeaker cones situated directly behind the target LEDs. In other conditions (spatial cuing), auditory stimuli were presented monaurally over headphones, while visual stimuli were presented in front of the subject (as in the studies of Klein, 1977, Posner et al., 1976, and others), in our case by still using the LEDs in front of the now-disconnected loudspeaker cones. The subjects made a spatially compatible discriminative response (pressing the left or right button) to indicate the lateral target location in all cases. The loudness of the targets was the same from the external loudspeakers and the headphones—75 dB(A), as measured from the subject's ear position.

Design and Procedure. The subjects were given 100 practice trials, followed by two test blocks of 240 experimental trials, for both the spatial-cuing and the no-spatial-cuing conditions, with order of spatial cuing blocked and counterbalanced across subjects. There were 200 (83.3%) valid trials and 40 (16.7%) invalid trials within each of the test blocks, in random order. The three within-subjects factors were presence or absence of spatial-cuing (headphones vs. external loudspeakers, respectively), target modality (auditory or visual), and validity (valid or invalid). The subjects were instructed at the beginning of every block of trials to attend to the modality indicated as likely by the central visual cue, which was presented on each trial, as in previous experiments. Furthermore, subjects were also told at the beginning of every block whether the auditory targets would be presented from the external loudspeaker cones for that block of trials or from the headphones.

Results

The usual latency criteria resulted in the removal of less than 0.1% of the trials. As noted by Ulrich and Miller (1994), in cases where exclusions are so minor, RT truncation does not introduce any spurious effects. The resulting mean RTs are shown in Table 4, along with corresponding error rates. A three-way within-subjects ANOVA was conducted on the RT data [spatial cuing (headphone vs. loudspeaker) × target modality (2) × cue validity (2)]. There was a highly significant main effect of modality [$F(1,13) = 49.4, p < .0001$], with subjects responding more rapidly to auditory targets than to visual targets. There was also a main effect of validity [$F(1,13) = 24.7, p = .0003$], revealing that subjects responded more rapidly on valid than on invalid trials. The interaction between validity and modality was significant [$F(1,13) = 4.9, p = .04$], with subjects showing a greater validity effect for visual targets than for auditory targets. More importantly, there was a significant interaction between spatial cuing and validity [$F(1,13) = 5.0, p = .04$], with subjects showing a greater validity effect in the headphone presentation conditions (mean invalid minus valid effect of 45 msec) than when target sounds were presented from external

Table 4
Mean Reaction Times (in Milliseconds), Their Standard Deviations, Mean Costs Plus Benefits, and Percentages of Errors for Auditory and Visual Targets in the Azimuth Discrimination Tasks in Experiment 4, Separated by Source of Presentation of Auditory Targets

	Cue Validity						
Target Modality	Valid			Invalid			Costs Plus Benefits
	M	*SD*	Errors	*M*	*SD*	Errors	
	Auditory Headphone Presentation						
Auditory	297	56	3.5%	337	71	4.3%	40*
Visual	339	41	2.2%	389	72	3.3%	50*
	Auditory External Loudspeaker Presentation						
Auditory	288	57	2.4%	315	64	2.3%	27*
Visual	329	50	2.1%	370	69	2.4%	41*

Note—By t test pairwise comparison: $^*p < .01$.

loudspeakers (mean effect of 34 msec). None of the other effects or interactions were significant [for spatial cuing, $F(1,13) = 2.8, p = .12$; for all other interactions, $F < 1$]. An equivalent ANOVA on the error data revealed no significant effects or interactions [for validity, $F(1,13) = 1.7, p = .21$; for modality, $F(1,13) = 1.3, p = .27$; for spatial cuing, $F(1,13) = 1.0, p = .33$; for spatial cuing × validity, $F(1,13) = 2.8, p = .12$; and for spatial cuing × modality, $F(1,13) = 2.4, p = .14$; for all other terms, $F < 1$]. It should be noted that although there were no significant effects in the analysis of errors, the trend was for larger costs plus benefits (i.e., invalid minus valid differences) in error data for the headphone blocks, where position was confounded with modality. This allows us to rule out speed–accuracy tradeoffs for the significantly larger cuing effects in RTs with headphones versus external loudspeakers.

Discussion

The results of Experiment 4 replicate and extend those from our previous studies, again showing more rapid responses when target modality is validly precued. More importantly, the results also show a significant interaction between the size of this modality-cuing effect and whether or not spatial information was also given by the modality cue. Subjects showed a significantly larger RT advantage ($M = 45$ msec) from knowing both the likely modality *and* the likely target position (at the headphones vs. in front of the subject) than from knowing just the modality when all target events were presented at equivalent external loci ($M = 34$ msec). This result shows that subjects in many previous modality-cuing experiments, where auditory and visual targets were presented from different locations, may have been using the modality cue to direct their attention both to a particular modality and to the most likely target location. That is, what has been described previously as the benefits caused solely by attending to a particular modality may actually have represented some unknown combination of modality cuing plus spatial cuing benefits. The present experiment shows that these two influences on performance can be separated by an appropriate method.

GENERAL DISCUSSION

Previous studies of attention to audition and vision have reported that many judgments improve when people are validly precued concerning target modality. Although this has been taken as showing modality selection, numerous alternative accounts are possible. First, modality-cuing effects in detection tasks (e.g., Boulter, 1977; Guttentag, 1985; Hohnsbein et al., 1991; Kristofferson, 1965; Mowrer et al., 1940; Phipps-Yonas, 1984; Simpson, 1972) may merely reflect criterion shifts (Mulligan & Shaw, 1981; Shaw, 1984). Likewise, studies that report an RT benefit in discriminations without providing error rates (e.g., Simpson, 1972; Verleger & Cohen, 1978) might similarly reflect criterion shifts that produce speed-accuracy tradeoffs.

Second, response priming could account for the modality-cuing effects reported in tasks requiring a modality discrimination (e.g., Parasuraman, 1985; Verleger & Cohen, 1978). Third, the use of a blocked-cuing design in many studies (Klein, 1977; Posner et al., 1976; Verleger & Cohen, 1978) has led to a confound between stimulus-driven MSEs, governed by the sequential relations between successive target stimuli, and endogenous attentional factors that depend on expectancies (see Dinnerstein & Zlotogura, 1968). Finally, all of these studies plus many others (e.g., Alho et al., 1992, 1994; Eijkman & Vendrik, 1965; Hackley et al., 1990; Harvey, 1980; LaBerge, 1973; LaBerge et al., 1970; Klein, 1977; Kristofferson, 1965; Münte et al., 1993; Posner et al., 1976; Shiffrin & Grantham, 1974; Woods et al., 1992) suffer from the presentation of auditory and visual targets from very different locations. This means that modality cues effectively provide spatial information as well, about the likely target location. It is then uncertain what proportion of the advantages from modality cuing in these studies is due to space-based versus modality-based attention.

These methodological problems seem particularly unfortunate, given the recent interest in apparent pathologies of attention toward particular sensory modalities among various clinical populations such as schizophrenics, autistics, and cerebellar patients (e.g., Ciesielski et al., 1990, 1995; Courchesne et al., 1993; Ferstl et al., 1994). Our review shows that, in fact, the various modality-cuing effects that have been examined by these clinical studies may not reflect attentional phenomena at all (i.e., they might all just reflect criterion shifts, response priming effects, or stimulus-repetition priming effects, as described in our introduction). Alternatively, they might all reflect mechanisms of *spatial* selection rather than of modality selection.

In the experiments reported here, we examined whether modality-cuing effects would be found in normals when all these various confounds were removed. We used an adaptation of Posner et al.'s (1976) paradigm, where a symbolic cue predicts the probable target modality on a trial-by-trial basis. Experiment 1 found that detection responses for auditory and visual targets were faster when modality was correctly cued. Analysis of catch-trial data (in which a cue but no target was presented) showed no tendency for a higher false-alarm rate when modality was cued, but subtle criterion-shift accounts remained difficult to rule out since false alarms could not be unambiguously attributed to one modality or the other (see note 1).

Accordingly, the remainder of our studies used discrimination tasks. Experiment 2 required a color discrimination for visual targets and an intensity discrimination for auditory targets. Once again, clear advantages were reported following valid cues to target modality. However, the subjects may have used the cue simply in order to reconfigure their task set (cf. Allport et al., 1994; Dixon & Just, 1986; Rogers & Monsell, 1995) rather than to direct their attention to one or another sensory modality per se. This seemed particularly likely because very different stimulus–response mappings were used for the auditory versus visual tasks.

To reduce the likelihood of this confound, subjects made a comparable spatial discrimination response for targets in either modality in our subsequent studies. Performance remained faster and more accurate for stimuli in the cued modality. This provides stronger evidence that cuing leads to preferential processing in the attended modality, rather than merely a remapping of stimulus categories to responses.

Our first three studies deliberately presented auditory and visual targets from comparable external locations. In the final experiment, some conditions deliberately reintroduced the confound between modality and location that had been inadvertantly present in most previous studies of modality cuing. For half of the experiment, subjects made left/right discriminations for sounds presented over headphones and lights presented from in front of them (as in Klein, 1977; Posner et al., 1978; and many other prior studies). In the other half of the study, sounds for the left/right discrimination were presented from loudspeakers located at the visual stimuli. The size of the modality-cuing effect was significantly greater in the headphones condition (where lights were in front but sounds at the head) than when targets in both modalities came from comparable external locations in front of the subjects. This provides empirical support for our claim that most previous modality-cuing experiments, both clinicial and normal, will have systematically overestimated the size of any modality-cuing benefits by confounding modality cuing with inadvertant spatial cuing.

As noted earlier, definitions of what would constitute a common task across modalities (or even within a single modality) are rare (see Rogers & Monsell, 1995). We hope that the spatial-discrimination task used in Experiments 3 and 4 may provide one example of a task that is as nearly identical across the two modalities as is possible, given the unavoidable need to present stimuli in different modalities when examining the current issues. Subjects were required to make a response that was highly compatible with targets in both modalities, and to do so in order to signal their discrimination of an attribute (location) that has been argued to rely on a common representation across hearing and vision (Auerbach & Sperling, 1974). At the very least, our localization tasks provide an intuitively more similar task environment for the two modalities than that used in Experiment 2, where subjects were required to make one response to quiet sounds and red lights and the other response to loud sounds and yellow lights. Here, the stimulus-response mapping seems entirely arbitrary and quite different for the two modalities, so that the modality-cuing effects might plausibly reflect complex task reconfiguration rather than selective attention to a particular sensory modality. Ultimately, there seems to be no decisive way of resolving the involvement of task reconfiguration in modality cuing when using just behavioral measures, other than by making such involvement increasingly implausible, as we have tried to do. However, ERP studies, which measure the activity in the neural systems underlying behavior, provide a further line of evidence which appears to support an attentional account for some effects of modality cuing.

The results of several ERP studies provide converging evidence that focusing on a particular sensory modality can result in the enhanced processing of stimuli in that modality. These studies typically examine averaged changes in electrical activity against time, measured by electrodes on the subject's scalp, as a function of the stimuli presented to the subject and of whether or not the subject is instructed to attend to these stimuli. Results from numerous ERP studies suggest that selective attention can result in selective amplitude enhancement of processing within modality-specific neural areas (e.g., Alho et al., 1992; Hackley et al., 1990; Hillyard, Simpson, Woods, Van Voorhis, & Münte, 1984; Woods et al., 1992; Woods, Alho, & Algazi, 1993). This enhancement of processing within primarily modality-specific sensory areas clearly favors an attentional interpretation of modality cuing, in terms of preferential sensory processing for stimuli within the cued modality, over an account purely in terms of endogenous task-set reconfiguration, which is widely held to depend on amodal control areas, such as the frontal lobes (e.g., Shallice, 1988).

However, there are two important caveats to be placed on the majority of prior ERP studies on this issue. First, we are aware of only one study, by Hillyard et al. (1984), that presented auditory and visual stimuli from comparable locations. In all of the other ERP studies, auditory and visual stimuli were inadvertantly presented from different locations, and so most of the ERP results may just reflect the effects of spatial shifts of attention rather than the effects of attending to a particular modality. Second, it is unclear whether the enhanced neural activity revealed in the focused-attention conditions by ERP measures reflects a true perceptual benefit for targets in the expected modality or merely a criterion shift. It would therefore be extremely useful in future studies to combine the behavioral methods introduced here with various neuroimaging techniques, such as ERP, PET, or fMRI.

REFERENCES

Alho, K., Woods, D. L., & Algazi, A. (1994). Processing of auditory stimuli during auditory and visual attention as revealed by event-related potentials. *Psychophysiology*, **31**, 469-479.

Alho, K., Woods, D. L., Algazi, A., & Näätänen, R. (1992). Intermodal selective attention: II. Effects of attentional load on processing of auditory and visual stimuli in central space. *Electroencephalography & Clinical Neurophysiology*, **82**, 356-368.

Allport, D. A., Styles, E. A., & Hsieh, S. (1994). Shifting intentional set: Exploring the dynamic control of tasks. In C. Umiltà & M. Moscovitch (Eds.), *Attention and performance XV: Conscious and nonconscious information processing* (pp. 421-452). Cambridge, MA: MIT Press.

Auerbach, C., & Sperling, P. (1974). A common auditory-visual space: Evidence for its reality. *Perception & Psychophysics*, **16**, 129-135.

Boulter, L. R. (1977). Attention and reaction times to signals of uncertain modality. *Journal of Experimental Psychology: Human Perception & Performance*, **3**, 379-388.

Ciesielski, K. T., Courchesne, E., & Elmasian, R. (1990). Effects of focused selective attention tasks on event-related potentials in autistic and normal individuals. *Electroencephalography & Clinical Neurophysiology*, **75**, 207-220.

Ciesielski, K. T., Knight, J. E., Prince, R. J., Harris, R. J., & Handmaker, S. D. (1995). Event-related potentials in cross-modal divided attention in autism. *Neuropsychologia*, **33**, 225-246.

Courchesne, E., Akshoomoff, N., Townsend, J., Yeung-Courchesne, R., Lincoln, A., James, H., Haas, R., Schreibman, L., & Lau, L. (1993). Impairment in shifting attention in autistic and cerebellar patients. In S. H. Broman & J. Grafman (Eds.), *Atypical cognitive deficits in developmental disorders: Implications for brain function* (pp. 67-83). Hillsdale, NJ: Erlbaum.

Dinnerstein, A. J., & Zlotogura, P. (1968). Intermodal perception of temporal order and motor skills: Effects of age. *Perceptual & Motor Skills*, **26**, 987-1000.

Dixon, P., & Just, A. M. (1986). A chronometric analysis of strategy preparation in choice reactions. *Memory & Cognition*, **14**, 488-500.

Driver, J., & Spence, C. J. (1994). Spatial synergies between auditory and visual attention. In C. Umiltà & M. Moscovitch (Eds.), *Attention and performance XV: Conscious and nonconscious information processing* (pp. 311-331). Cambridge, MA: MIT Press.

Eijkman, E., & Vendrik, J. H. (1965). Can a sensory system be specified by its internal noise? *Journal of the Acoustical Society of America*, **37**, 1102-1109.

Ferstl, R., Hanewinkel, R., & Krag, P. (1994). Is the modality-shift effect specific for schizophrenia patients? *Schizophrenia Bulletin*, **2**, 367-373.

Guttentag, R. E. (1985). A developmental study of attention to auditory and visual signals. *Journal of Experimental Child Psychology*, **39**, 546-561.

Hackley, S. A., Woldorff, M., & Hillyard, S. A. (1990). Cross-modal selective attention effects on retinal, myogenic, brainstem, and cerebral evoked potentials. *Psychophysiology*, **27**, 195-208.

Hafter, E. R., & Bonnel, A.-M. (1995, June). *Shared attention in detection and identification.* Paper presented at the 129th Meeting of the Acoustical Society of America (Washington, DC).

Hannes, M., Sutton, S., & Zubin, J. (1968). Reaction time: Stimulus uncertainty with response certainty. *Journal of General Psychology*, **78**, 165-181.

Harvey, N. (1980). Non-informative effects of stimuli functioning as cues. *Quarterly Journal of Experimental Psychology*, **32**, 413-425.

Hillyard, S. A., Simpson, G. V., Woods, D. L., Van Voorhis, S., & Münte, T. F. (1984). Event-related brain potentials and selective attention to different modalities. In F. Reinoso-Suárez & C. Ajmone-Marson (Eds.), *Cortical integration* (pp. 395-414). New York: Raven Press.

Hohnsbein, J., Falkenstein, M., Hoormann, J., & Blanke, L. (1991). Effects of crossmodal divided attention on late ERP components. 1. Simple and choice reaction tasks. *Electroencephalography & Clinical Neurophysiology*, **78**, 438-446.

Jonides, J. (1981). Voluntary versus automatic control over the mind's eye's movement. In J. Long & A. Baddeley (Eds.), *Attention and performance IX* (pp. 187-203). Hillsdale, NJ: Erlbaum.

Klein, R. M. (1977). Attention and visual dominance: A chronometric analysis. *Journal of Experimental Psychology: Human Perception & Performance*, **3**, 365-378.

Klein, R. M., Kingstone, A., & Pontefract, A. (1992). Orienting of visual attention. In K. Rayner (Ed.), *Eye movements and visual cognition: Scene perception and reading* (pp. 46-65). New York: Springer-Verlag.

Kraeplin, E. (1919). *Dementia praecox and paraphrenia.* Chicago: Medical Books.

Kristofferson, A. B. (1965). *Attention in time discrimination and reaction time* (NASA Contractors Report 194). Washington, DC: Office of Technical Services, U.S. Department of Commerce.

Kristofferson, M. W. (1967). Shifting attention between modalities. *Journal of Abnormal Psychology*, **72**, 388-394.

LaBerge, D. (1973). Identification of two components of the time to switch attention: A test of a serial and a parallel model of attention. In S. Kornblum (Ed.), *Attention and performance IV* (pp. 71-85). New York: Academic Press.

LaBerge, D., Van Gelder, P., & Yellott, J., Jr. (1970). A cueing technique in choice reaction time. *Perception & Psychophysics*, **7**, 57-62.

Mannuzza, S. (1980). Cross-modal reaction time and schizophrenic attentional deficit: A critical review. *Schizophrenia Bulletin*, **6**, 654-675.

Massaro, D. W., & Kahn, B. J. (1973). Effects of central processing on auditory recognition. *Journal of Experimental Psychology*, **97**, 51-58.

Massaro, D. W., & Warner, D. S. (1977). Dividing attention between auditory and visual perception. *Perception & Psychophysics*, **21**, 569-574.

Miller, J. O. (1988). A warning about median reaction time. *Journal of Experimental Psychology: Human Perception & Performance*, **14**, 539-543.

Mowrer, O. H., Rayman, N. N., & Bliss, E. L. (1940). Preparatory set (expectancy)—An experimental demonstration of its 'central' locus. *Journal of Experimental Psychology*, **26**, 357-372.

Mulligan, R. M., & Shaw, M. L. (1981). Attending to simple auditory and visual signals. *Perception & Psychophysics*, **30**, 447-454.

Münte, T. F., Blum, H., & Heinze, H.-J. (1993). Attentional orienting to visual targets after visual and auditory cues: An analysis with event-related brain potentials. *Zeitschrift EEG-EMG*, **24**, 225-233.

Parasuraman, R. (1985). Event-related brain potentials and intermodal divided attention. *Proceedings of the Human Factors Society*, **29**, 971-975.

Pashler, H., & Baylis, G. (1991). Procedural learning: 2. Intertrial repetition effects in speeded-choice tasks. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, **17**, 33-48.

Phipps-Yonas, S. (1984). Visual and auditory reaction time in children vulnerable to psychopathology. *Minnesota High-Risk Studies*, **6**, 312-319.

Posner, M. I., Nissen, M. J., & Klein, R. M. (1976). Visual dominance: An information-processing account of its origins and significance. *Psychological Review*, **83**, 157-171.

Posner, M. I., Nissen, M. J., & Ogden, W. C. (1978). Attended and unattended processing modes: The role of set for spatial location. In

H. I. Pick & E. Saltzman (Eds.), *Modes of perceiving and processing information* (pp. 137-157). Hillsdale, NJ: Erlbaum.

Rafal, R. D., Calabresi, P. A., Brennan, C. W., & Sciolto, T. K. (1989). Saccade preparation inhibits reorienting to recently attended locations. *Journal of Experimental Psychology: Human Perception & Performance*, **15**, 673-685.

Rist, F., & Cohen, R. (1987). Effects of modality shift on event-related potentials and reaction time of chronic schizophrenics. In R. Hohnson, Jr., J. W. Rohrbaugh, & R. Parasuraman (Eds.), *Current trends in event-related potential research* (pp. 738-745). Amsterdam: Elsevier.

Rist, F., & Thurm, I. (1984). Effects of intramodal and crossmodal stimulus diversity on the reaction time of chronic schizophrenics. *Journal of Abnormal Psychology*, **93**, 331-338.

Robin, D. A., & Rizzo, M. (1989). The effect of focal cerebral lesions on intramodal and cross-modal orienting of attention. In T. E. Prescott (Ed.), *Clinical aphasiology* (Vol. 18, pp. 61-74). Boston: College-Hill.

Robin, D. A., & Rizzo, M. (1992). Orienting of attention in audition and between audition and vision: Young and elderly subjects. *Journal of Speech & Hearing Research*, **35**, 701-707.

Rogers, D. R., & Monsell, S. (1995). Costs of a predictable switch between simple cognitive tasks. *Journal of Experimental Psychology: General*, **124**, 207-231.

Shallice, T. (1988). *From neuropsychology to mental structure*. Cambridge: Cambridge University Press.

Shaw, M. L. (1984). Division of attention among spatial locations: A fundamental difference between detection of letters and detection of luminance increments. In H. Bouma & D. G. Bouwhuis (Eds.), *Attention and performance X* (pp. 109-121). Hillsdale, NJ: Erlbaum.

Shiffrin, R. M., & Grantham, D. W. (1974). Can attention be allocated to sensory modalities? *Perception & Psychophysics*, **15**, 460-474.

Simpson, W. E. (1972). Latency of locating lights and sounds. *Journal of Experimental Psychology*, **93**, 169-175.

Spence, C., & Driver, J. (1994). Covert spatial orienting in audition: Exogenous and endogenous mechanisms. *Journal of Experimental Psychology: Human Perception & Performance*, **20**, 555-574.

Spence, C., & Driver, J. (1996). Audiovisual links in endogenous covert spatial attention. *Journal of Experimental Psychology: Human Perception & Performance*, **22**, 1005-1030.

Spence, C., & Driver, J. (1997). Audiovisual links in exogenous covert spatial orienting. *Perception & Psychophysics*, **59**, 1-22.

Spence, C., Driver, J., & Rogers, R. (1997). *Is there an attentional component to the MSE?* Manuscript in preparation.

Spring, B. J. (1980). Shift of attention in schizophrenics, siblings of schizophrenics, and depressed patients. *Journal of Nervous & Mental Disease*, **168**, 133-140.

Sutton, S., Hakerem, G., Zubin, J., & Portnoy, M. (1961). The effect of shift of sensory modality on serial reaction time: A comparison of schizophrenics and normals. *American Journal of Psychology*, **74**, 224-232.

Sutton, S., & Zubin, J. (1965). Effect of sequence on reaction time in schizophrenia. In A. T. Welford & J. E. Birren (Eds.), *Behavior, ageing and the nervous system* (pp. 562-597). Springfield, IL: Charles C. Thomas.

Ulrich, R., & Miller, J. (1994). Effects of truncation on reaction time analysis. *Journal of Experimental Psychology: General*, **123**, 34-80.

Verleger, R., & Cohen, R. (1978). Effects of certainty, modality shift and guess outcome on evoked potentials and reaction times in chronic schizophrenics. *Psychological Medicine*, **8**, 81-93.

Waldbaum, J. K., Sutton, S., & Kerr, J. (1975). Shifts of sensory modality and reaction time in schizophrenia. In M. L. Kietzman, S. Sutton, & J. Zubin (Eds.), *Experimental approaches to psychopathology* (pp. 167-176). New York: Academic Press.

Woods, D. L., Alho, K., & Algazi, A. (1992). Intermodal selective attention: 1. Effects on event-related potentials to lateralized auditory and visual stimuli. *Electroencephalography & Clinical Neurophysiology*, **82**, 341-355.

Woods, D. L., Alho, K., & Algazi, A. (1993). Intermodal selective attention: Evidence for processing in tonotopic auditory fields. *Psychophysiology*, **30**, 287-295.

Wundt, W. (1893). *Grundzüge der physiologischen Psychologie* [Foundations of physiological psychology] (4th ed.). Leipzig: Wilhelm Engelmann.

NOTE

1. The possibility that criteria were lowered in the expected modality and raised in the unexpected modality cannot be definitively ruled out, due to ambiguity concerning which modality induced any false-alarm response (i.e., when the button is pressed on a catch trial, this does not reveal whether the false alarm is visual or auditory). The suggested pattern of opposing criterion shifts in the two modalities might result in no significant differences being found between the false-alarm rates for the different conditions, as observed, even though subjects had in fact lowered their criteria for the expected modality. That is, an increase in the number of false alarms caused by lowered criteria for responding to events in the expected modality might have been offset by a decrease in false alarms caused by increased criteria for responding to events in the unexpected modality. Overall, such a pattern of differential criterion shifting could result in the same pattern of false alarms as would have been found if subjects' criteria had remained truly constant across conditions.

APPENDIX

Further analyses of Experiments 1–4 investigated any effects of target location on performance. In Experiments 1–3, targets could be presented from any of the four quadrants delineated by the main meridians (i.e., lower left, lower right, upper left, and upper right). Table A1 gives the mean RTs, their standard deviations, and the associated error rates (where appropriate) for each target quadrant in those studies. In Experiment 4, targets could be presented only from the left or right at an intermediate elevation.

An omnibus within-subjects ANOVA on the RT data for Experiment 1 had three factors [target quadrant (4), target modality (2), and cuing (3)]. This found a main effect of quadrant [$F(3,27) = 4.1, p = .02$]. A pairwise comparison t test revealed that this effect was due to faster responses in the lower right quadrant than in either the upper or lower left quadrants. Target quadrant did not interact with any of the other factors ($F < 1$ for all terms).

A similar analysis on RT data for Experiment 2 also found a quadrant effect [$F(3,33) = 5.3, p = .004$]. As confirmed by t tests, RTs were slower for targets in the upper left than in any other position, with a complementary trend in errors. Target quad-

Table A1
Mean Reaction Times (in Milliseconds), Their Standard Deviations, and Percentages of Errors for Auditory and Visual Targets in Experiments 1–3, Separated by Target Location

	Target Quadrant											
	Lower Left			Upper Left			Lower Right			Upper Right		
Experiment	*M*	*SD*	Errors	*M*	*SD*	Errors	*M*	*SD*	Errors	*M*	*SD*	Errors
1	314	70		317	69		306	71		311	71	
2	620	139	5.6%	661	157	7.5%	623	160	4.9%	626	136	4.8%
3	459	117	2.7%	481	115	2.8%	450	116	1.7%	452	111	1.4%

Note—Experiment 1, simple detection; Experiment 2, color intensity; Experiment 3, left/right or up/down.

rant did not interact with any of the other factors (all *F*s < 1.5). A similar ANOVA on the error data found no significant terms involving target quadrant (all *F*s < 1.5).

An omnibus within-subjects ANOVA on the RT data for Experiment 3 [target quadrant (4) × target modality (2) × validity (2)] found a main effect of target quadrant [$F(3,21) = 3.5, p = .03$], with RTs to upper left targets once again numerically slower than RTs to targets in any other position; in *t* test comparisons, this delay reached significance only against the lower right position ($p < .01$) and the upper right position ($p < .05$). The three-way interaction between target quadrant, modality, and validity was significant [$F(3,21) = 4.2$, $p = .02$]. This unexpected outcome was due to smaller validity effects for auditory targets when in the upper left position and for visual targets when in the lower left position, but the pattern was for valid advantages in all cases. None of the other terms in the RT analysis involving target quadrant were significant, and an analagous analysis of the error data also showed no sigificant effects involving quadrant.

In Experiment 4, there were only two possible target positions, left and right. An omnibus within-subjects ANOVA on the RT data had the four factors of side (2), modality (2), modality cuing (2), and auditory source (headphones vs. loudspeakers). Responses were faster for right targets (M = 324 msec) than for left targets (M = 341 msec) [$F(1,13) = 9.1, p < .01$]. Target side interacted with modality [$F(1,13) = 6.7, p = .02$] as the right-sided advantage emerged only for auditory targets (at $p < .01$ in a *t* test). None of the other terms involving target side reached significance. The error data showed a small trend for more errors to right auditory targets (M = 2.6%) than to left auditory targets (M = 2.0%; M = 1.5% for left visual targets and 1.6% for right visual targets), perhaps questioning whether the RT advantage for right sounds reflects a true advantage or merely a speed/error tradeoff. No term involving target side was significant in an omnibus ANOVA on the errors (all *F*s < 1.5).

These experiments were not designed to test any specific hypotheses regarding target location. The position analyses are provided here solely for completeness, at the request of a reviewer (Ray Klein). Nevertheless, the general pattern can be summarized as suggesting an advantage for right locations over left and for lower positions over upper. More importantly for present purposes, an advantage for valid over invalid trials was apparent at all target positions.

(Manuscript received February 1, 1996;
revision accepted for publication May 17, 1996.)