Visual Localization Ability Influences Cross-Modal Bias

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Abstract

■ The ability of a visual signal to influence the localization of an auditory target (i.e., ‘‘cross-modal bias’’) was examined as a function of the spatial disparity between the two stimuli and their absolute locations in space. Three experimental issues were examined: (a) the effect of a spatially disparate visual stimulus on auditory localization judgments; (b) how the ability to localize visual, auditory, and spatially aligned multisensory (visual–auditory) targets is related to cross-modal bias, and (c) the relationship between the magnitude of cross-modal bias and the perception that the two stimuli are spatially ‘‘unified’’ (i.e., originate from the same location). Whereas variability in localization of auditory targets was large and fairly uniform for all tested locations, variability in localizing visual or spatially aligned multisensory targets was much smaller, and increased with increasing distance from the midline. This trend proved to be strongly correlated with biasing effectiveness, for although visual–auditory bias was unexpectedly large in all conditions tested, it decreased progressively (as localization variability increased) with increasing distance from the midline. Thus, central visual stimuli had a substantially greater biasing effect on auditory target localization than did more peripheral visual stimuli. It was also apparent that cross-modal bias decreased as the degree of visual–auditory disparity increased. Consequently, the greatest visual–auditory biases were obtained with small disparities at central locations. In all cases, the magnitude of these biases covaried with judgments of spatial unity. The results suggest that functional properties of the visual system play the predominant role in determining these visual–auditory interactions and that cross-modal biases can be substantially greater than previously noted. ■

INTRODUCTION

Perception often involves integrating information from different senses, a process that normally results in a single unified experience. However, the perceptual product of this multisensory synthesis does not necessarily reflect an equal weighting of inputs. For instance, a visual stimulus can more readily bias one’s judgment of auditory location than the reverse. This effect, known as the ‘‘ventriloquist effect’’ (see Howard & Templeton, 1966), is quite robust, and is apparent even when pairing neutral, seemingly unrelated, stimuli such as spots of light and noise bursts (Lewald, Ehrenstein, & Guski, 2001; Slutsky & Recanzone, 2001; Bertelson & Radeau, 1981; Bertelson & Aschersleben, 1998; Radeau & Bertelson, 1987; Welch & Warren, 1986; Radeau, 1985; Bermant & Welch, 1976).

To better understand this striking cross-modal phenomenon, many investigators have imposed varying degrees of spatial disparity between visual and auditory stimuli and assessed whether they are still perceived as originating from the same location (i.e., appear ‘‘spatially unified’’) (Lewald et al., 2001; Slutsky & Recanzone, 2001; Bertelson & Aschersleben, 1998; Radeau & Bertelson, 1987; Thurlow & Rosenthal, 1976; Choe, Welch, Guilford, & Juola, 1975; Jack & Thurlow, 1973; Thurlow & Jack, 1973).

Others have examined how a visual signal alters the perceived location of an auditory target by using a variety of localization tasks (Radeau, 1985; Warren, 1979; Bermant & Welch, 1976; Weerts & Thurlow, 1971), and in one case, these two judgments have been examined in the same paradigm (Bertelson & Radeau, 1981). As a result of these investigations, there is a good deal of evidence indicating that the degree of cross-modal bias can be significantly decreased by increasing the disparity between the visual and auditory stimuli (Bertelson & Radeau, 1981; Bermant & Welch, 1976), decreasing the relative intensity of the visual stimulus (Radeau, 1985), or simply informing the subjects of the existence of a disparity between the stimuli (Warren, 1979; Welch, 1972).

However, what is not apparent from these studies is the impact of the specific location (i.e., central, paracentral, peripheral) of these stimuli on cross-modal bias, a factor that seems likely to play a significant role in this phenomenon. For example, visual performance on psychophysical tasks is known to change substantially as a function of target location (Carrasco, Evert, Chang, & Katz, 1995; Mateeff & Gourevich, 1983), and to parallel the geometric distortion in the representation of visual space (Carrasco & Frieder, 1997; Rovamo & Raninen,

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1990; Virsu & Rovamo, 1979). Thus, the primary focus of the current experiments was on the spatial determinants of cross-modal bias. It included an examination of how visual–auditory bias is affected by the disparity between the signals at different locations in space, and the association between the strength of the biases produced by manipulating these spatial variables and the perception that the two signals are spatially aligned.

Portions of these results have been reported previously in abstract form (Hairston, Vaughan, Wallace, Stein, & Schirillo, 2001).

RESULTS

In Experiment 1a, the subjects' task was to judge the location of an auditory target in the presence of a

Table 1. Standard Deviation in Localization and Average Bias for Each Subject, Experiments 1a and 2

		Standard Deviation in Localization (°)			
Experiment	*Subject*	*Target Position*	*Auditory*	*Multisensory*	*Average Bias (%)*
1a	BS	0	9.31	0.78	105.92
		10	8.24	1.88	83.43
		30	7.97	4.67	74.90
	JC	0	6.29	5.63	5.80
		10	10.38	7.12	13.03
		30	13.79	5.66	5.64
	KS	0	8.15	0.88	147.17
		10	7.73	1.99	134.87
		30	12.56	3.31	90.92
	RS	0	4.48	0.42	102.55
		10	6.71	1.60	99.97
		30	8.19	4.81	86.49
	RV	0	4.07	0.58	114.90
		10	12.52	1.26	100.04
		30	12.77	4.85	85.39
2	JH	0	15.43	3.57	119.74
		10	13.35	3.51	101.57
		30	11.78	3.71	75.34
	KC	0	14.82	11.86	39.77
		10	18.89	12.35	6.88
		30	32.69	12.94	14.89
	MA	0	10.64	1.56	136.63
		10	8.63	2.98	123.11
		30	11.22	4.98	79.29
	NG	0	8.65	3.32	59.47
		10	6.90	4.23	60.62
		30	6.49	6.42	56.81
	TG	0	8.43	4.47	27.23
		10	5.87	5.83	15.11
		30	7.33	7.52	−10.08

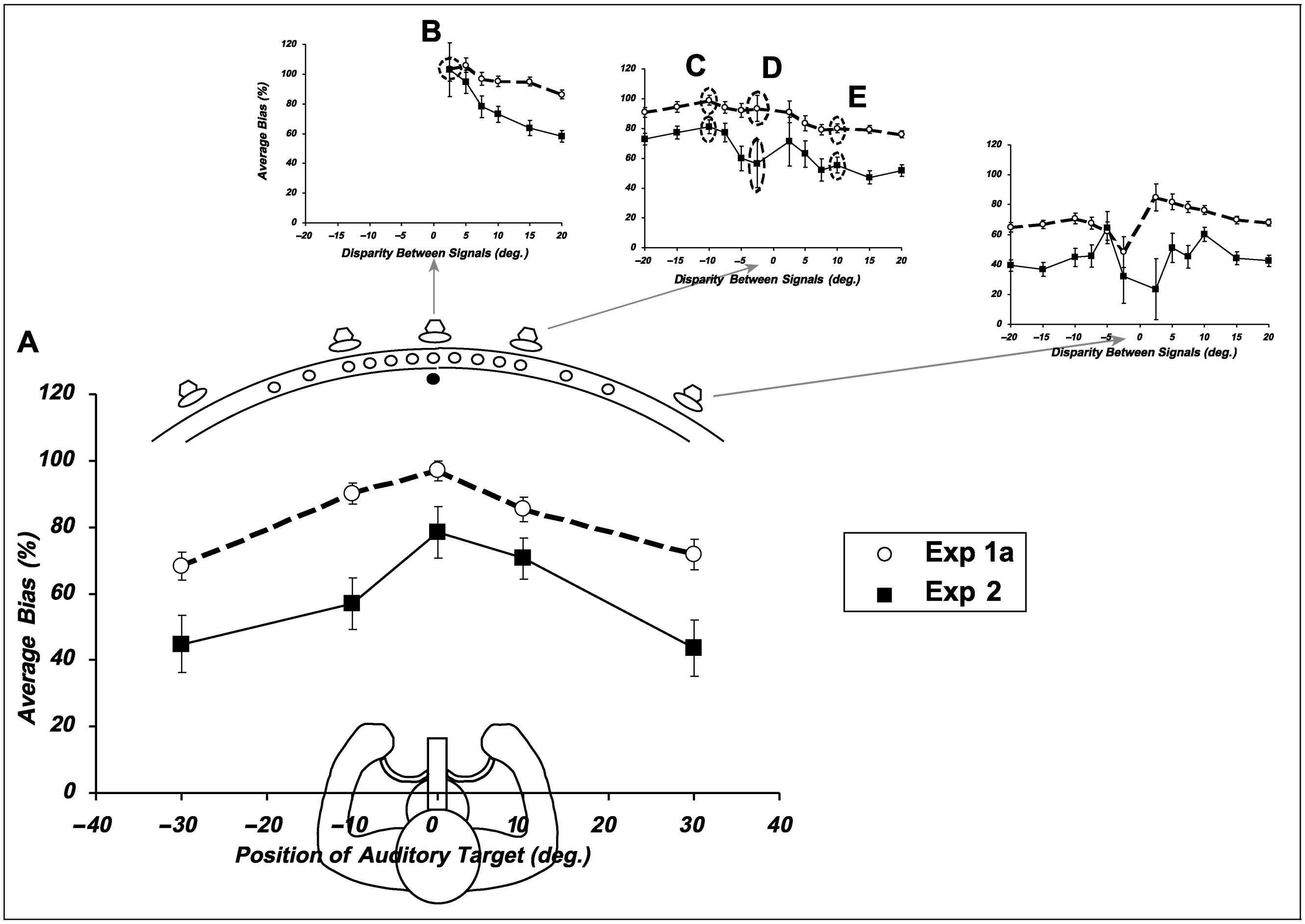

Figure 1. Bias declines with increasing target eccentricity. Large graph (A) shows this effect collapsed across all spatial disparities, and schematically represents the paradigm and the locations of a subset of fixation (small filled circle), visual (open circles), and auditory target (icons of speaker) stimuli. The three inset graphs plot bias as a function of disparity for three different target locations, 0°, 10°, and 30°. Note that the most bias occurs with an auditory target at midline, and the visual stimulus slightly offset (i.e., 2.5°; B). For targets located at 10°, bias is greatest when the visual signal is 10° nasal, placing it at midline (C). Note that this amount of bias is even greater than when the stimuli are close together (D). In addition, for the same target, there is much less bias when the light is temporal to the target by the same amount (i.e., 10°; E). For peripheral targets (i.e., 30°, rightmost inset), bias is generally lower than for more central targets. Error bars represent the average within-subjects *SEM*.

simultaneously presented, but spatially disparate, visual stimulus. Disparity was varied randomly from 2.5° to 20°, and all stimuli were presented within the central 100° (50° either side of center) of space. In Experiment 1b, baseline data were gathered to assess localization performance using the same stimuli, but in this case, the target could be the visual stimulus alone, the auditory stimulus alone, or a spatially coincident visual–auditory stimulus pair (i.e., 0° disparity). These data provided baseline measures of localization variability, which served as the comparators for the data gathered in Experiment 1a. Experiment 2 was similar to Experiment 1a, but included a report of perceived spatial unity; subjects not only located the auditory target, but also indicated, via a footswitch, whether the visual and auditory stimuli appeared to originate from the same location. To examine the possibility that judgments of auditory localization could somehow affect this perceptual judgment, a third experiment (Experiment 3) was added in which subjects were asked to only report on perceived spatial unity (i.e., no localization was required).

For localization judgments involving spatial disparity, bias was calculated as the normalized error (in degrees) in the localization of the auditory stimulus. ''Percent bias'' reflects this error as a percentage of the disparity between the visual and auditory stimuli (see Methods). Judgments of ''unity'' in each condition were also expressed as a percentage and were calculated by dividing the number of reports of unity by the number of trials.

Visual–Auditory Bias is Present at All Disparities

For both Experiments 1a and 2, the presence of a visual stimulus produced a significant bias in the localization of the auditory target. In each case, the judgments of the auditory target's location were biased toward the visual stimulus, and significant bias was noted even when visual–auditory disparities were substantial. For

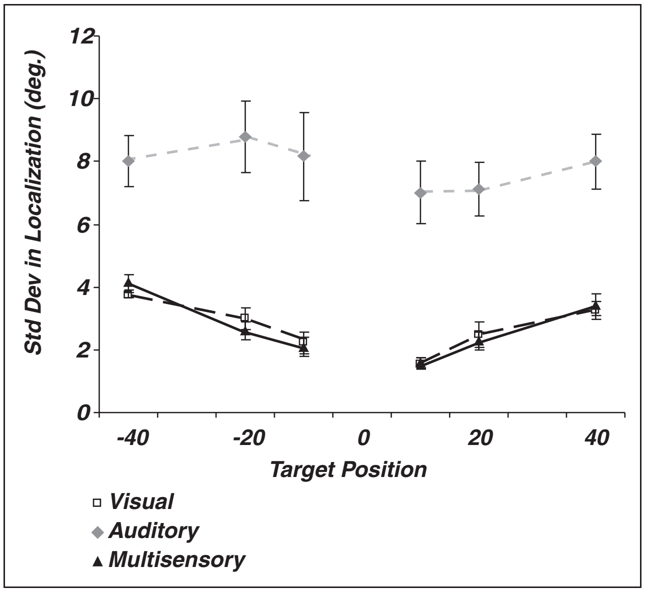

Figure 2. Localization variance is equivalent for visual and multisensory targets, and increases with target distance from midline. However, localization variance is greater for auditory targets at all locations. Data are plotted from Experiment 1b. Error bars represent the between-subjects *SEM*.

instance, when the disparity was 20°, the auditory target was judged to be located on average 15.4° toward the visual stimulus (77% bias) in Experiment 1a [$t(4) = 4.17$, $p < .05$], and 10.6° toward the visual stimulus (53% bias) in Experiment 2 [$t(4) = 2.52$, $p < .05$]. Although such cross-modal bias was reliably evoked in all subjects, the degree of interindividual variability was substantial, with some subjects consistently showing extreme bias (KS, MA), and others consistently showing far more modest bias (JC, TG) (see Table 1).

Spatial Factors Influence Visual–Auditory Bias

Figure 1 shows the average bias for each auditory target position as a function of the spatial disparity between the signals. For auditory targets at midline, bias decreased with increasing disparity (i.e., increasing eccentricity of the visual stimulus). Although less clear for more eccentric auditory target locations (i.e., ±10°), a similar trend is observed. Furthermore, regardless of auditory target location, bias was greatest when the visual signal was in central space. For example, when the auditory target was at midline (0°), the greatest bias was seen when the visual signal was also very close to midline (i.e., 2.5° offset, see Figure 1B). This shows the impact of proximity on bias. However, for the ±10° auditory target locations, the greatest bias occurred when the visual stimulus was at midline (−10° disparity, Figure 1C), rather than when it was only slightly offset from the auditory target (Figure 1D). Furthermore, when the visual stimulus was 10° peripheral to this auditory target (Figure 1E), the bias was less than when it was 10° central to it.

Collapsing the data across disparities showed that the average bias decreased with auditory target eccentricity (Figure 1A). This difference was significant for both Experiment 1a [$F(2,8) = 6.96, p < .05$], and Experiment 2 [$F(2,8) = 8.37$, $p < .05$]. The trends in how bias changes as a function of both disparity and target location are similar for both experiments; however, those subjects who simultaneously evaluated spatial unity averaged less bias (Experiment 2; 58.9%) than those who did not (Experiment 1a; 82.5%).

Localization Variability in Nondisparate Conditions

In Experiment 1b, localization variability, measured as the standard deviation of localization performance for each

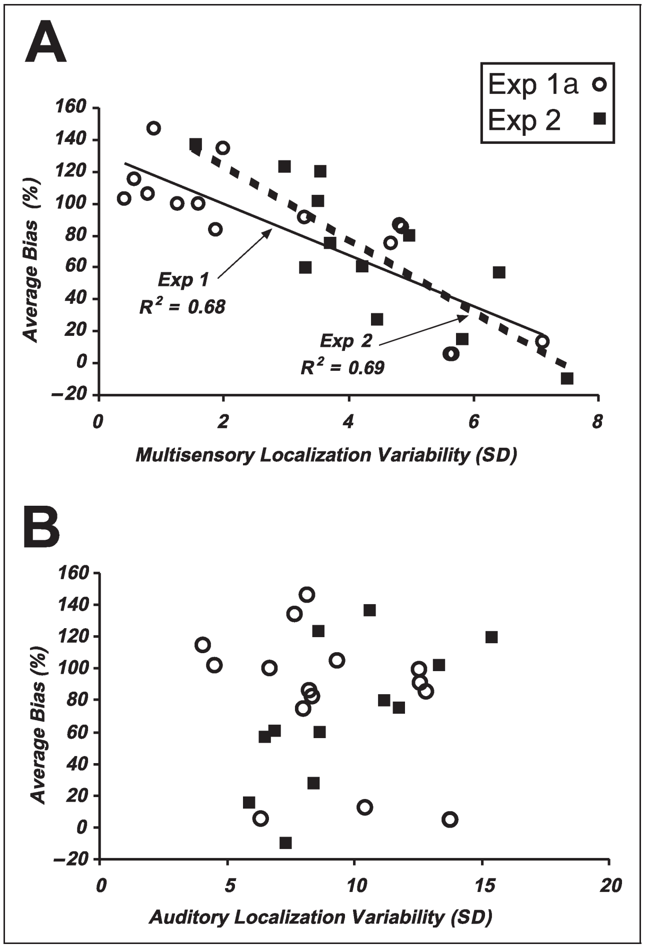

Figure 3. The variability in localizing spatially coincident multisensory targets and the amount of bias associated with a disparate visual signal for a target in the same location are negatively correlated (A). Open circles and solid line represent the data from Experiment 1a. Closed circles and dashed line represent the data from Experiment 2. Because localization variability is nearly identical for multisensory and visual stimuli, approximately the same correlation will apply to visual localization variability. In contrast, there is no consistent relationship between variability in localizing an auditory target and bias (B).

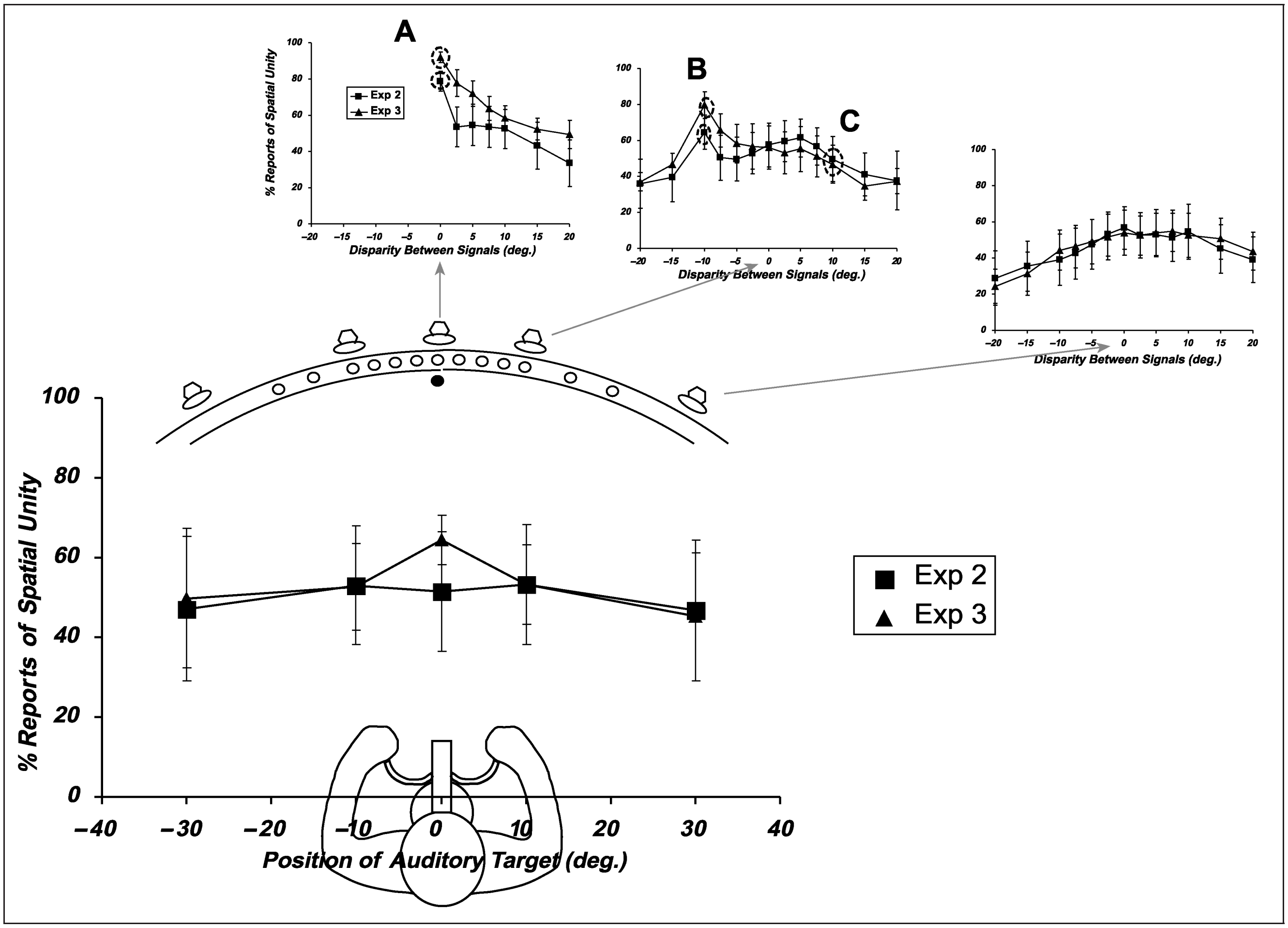

Figure 4. When collapsed across all locations, there is no apparent relationship between reports of spatial unity and the location of the auditory target (large graph; conventions are the same as for Figure 1). However, when the auditory target is at midline, reports of spatial unity occur most often with a coincident visual stimulus (A), and decline with increasing disparity. For more eccentric target locations (i.e., ±10°), spatial unity is reported more often when the visual signal is central to the sound by 10° (B) than when it is peripheral to the sound by the same amount (C). However, the rightmost inset shows that this is not the case when the target is further peripheral (e.g., ±30°). Error bars represent the between-subjects *SEM*.

condition (visual, auditory, coincident multisensory), was determined for each target location (Figure 2). Responses for the 0° target were excluded from analysis because they did not require any movement of the laser pointer, producing a floor effect in the data. Variability for visual and spatially coincident multisensory localization was statistically equivalent at each target location [$t(4) = .289$, $p > .05$], and increased as target eccentricity increased. Thus, localization performance was significantly more variable for peripheral (±40°) than for central (±10°) targets [$t(4) = 5.61$, $p < .05$, visual; $t(4) = 3.21$, $p < .05$, multisensory]. In contrast, auditory variability was significantly larger overall than visual [$t(4) = 4.99$, $p < .05$] or multisensory [$t(4) = 5.63$, $p < .05$] variability, and changed little as a function of target location. These observations suggest that the trend in multisensory localization variability is attributable to the visual stimulus. Similar trends were found in the experiments involving cross-modal disparities (Experiments 1a and 2, Table 1), with a significant increase in variability with increased eccentricity, comparing ±10° to ±30° [$t(4) = 9.31, p < .01$, Experiment 1a; $t(3) = 3.92$, $p < .05$, Experiment 2].[1] Because the auditory stimulus was always the target in these conditions, direct measures of visual localization variability are not available.

Some possible confounding variables in these studies are the potential contributions of motor and/or memory elements to localization variability. Although the data shown in Figure 1 suggest a minimal motor contribution to response variability (note in Figure 1 the similarity in bias variability for equal disparities on either side of ±10° targets, C vs. E, even though these involve very different movement distances), we tested this further in an additional control group (data not shown). Here, subjects were asked to localize visual signals under conditions identical to those mentioned previously, except that the trial began with the laser pointed 30° to the left (instead of directly ahead). In this circumstance, if movement amplitude contributed significantly to response variability, the expectation would be a systematic increase in variability for targets at increasingly rightward locations. In contrast, variability for eccentric (i.e., ±20°) targets was equivalent on both sides of space, and was greater than for those in central (0°) space. Additionally, while the time to complete localization of the most peripheral targets (±40°) averaged 1200 msec from the stimulus offset, previous work using a similar paradigm (Roberson et al., 2001) has shown that much larger delays are required in order to affect localization ability under these conditions. Together, these controls suggest that the predominant influence on localization variability is the nature of the sensory stimuli.

Visual–Auditory Bias is Correlated with Localization Variability

Table 1 indicates that the variability in localizing spatially coincident multisensory targets is inversely correlated with the average bias obtained. This is more apparent in Figure 3A, where for every subject, at every target position, the average visual–auditory bias was plotted as a function of variability in localizing a spatially coincident multisensory target. A linear regression revealed a significant correlation between these factors (Experiment 1a, $r^2 = .68$, $p < .05$; Experiment 2, $r^2 = .69$, $p < .05$). This correlation, in conjunction with the similarity in localization variability for multisensory and visual stimuli (Experiment 1b, Figure 2), suggests a relationship between the accuracy with which a visual stimulus is localized (i.e., low variability) and the amount of bias it exerts over an auditory target. In contrast, no such relationship was seen between bias and localization variability for auditory targets (Figure 3B; $r^2 = .10$, $p > .05$, Experiment 1a; $r^2 = .29$, $p > .05$, Experiment 2).

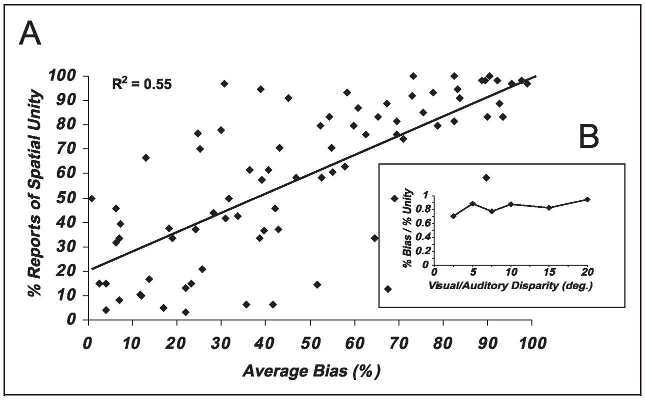

Figure 5. Reports of spatial unity and the average visual bias of auditory localization are positively correlated. Inset shows that this relationship between unity and bias is relatively consistent across all disparities tested (B).

Reports of Spatial Unity and Localization Bias

Reports of spatial unity followed a pattern similar to that found for localization bias (see Figure 1). Thus, the overall likelihood of reporting spatial unity was highest when both stimuli were in central space. However, this was particularly dependent on the midline location of the visual stimulus (Figure 4A). It was evident even when the auditory targets were at ±10°; that is, with equal spatial disparities the biasing effects were significantly greater when the visual stimulus was central (Figure 4B) rather than peripheral to the auditory targets (Figure 4C). Localization bias and reports of spatial unity were found to be significantly correlated ($r^2 = .55$, $p < .05$; Figure 5A), thereby underscoring the relationship between these two measures: When localization bias was high, subjects were more likely to report that the signals were spatially unified. This trend was consistent across all disparities tested (Figure 5B).

DISCUSSION

A spatially disparate neutral visual stimulus was found to have a strong impact on a subject's ability to localize an auditory target, even with disparities as great as 20°. Although the presence of visual–auditory localization bias has been noted previously (see Radeau, 1985; Radeau & Bertelson, 1987; Bertelson & Radeau, 1981), the magnitude of the bias induced in the present study was far larger than that expected based on previous reports. This difference most likely reflects the sensitivity of this effect to differences in stimulus parameters and/or cognitive factors. Previous studies used longer stimulus durations, which may have increased target salience and/or decreased the ambiguity of their locations, thereby minimizing their susceptibility to apparent translocation. Furthermore, the present results, like those of previous studies (Warren, 1979; Welch, 1972), showed that cross-modal localization bias was highly sensitive to the instructions subjects received. Instructing subjects to attend to the spatial relationships between the stimuli in the present study significantly decreased cross-modal bias. Taken together, these results suggest that the ventriloquist effect is strongly dependent on both the specifics of the sensory environment and on higher-order processes, that the effect is remarkably robust in a host of circumstances, and that it can be induced with stimuli having little real-world significance.

Although counterintuitive, bias was not related to the ability to locate auditory targets. Rather, in all circumstances examined, cross-modal bias was strongly dependent on the location of the visual (i.e., biasing) stimulus. Invariably, bias was greatest when the visual stimulus was in central visual space, specifically, at or near midline. It seems likely that this reflects the brain's magnified representation of central visual space (Brindley & Lewin, 1968). Consistent with this interpretation (see also Carrasco et al., 1995; Mateeff & Gourevich, 1983) is the current finding that accuracy in visual target location decreased (i.e., variability increases) substantially as the target shifted from central to peripheral space, a change that was directly related to perceptual ambiguity. When accuracy in localization decreased, perceptual ambiguity increased. Thus, it seems likely that the degree to which the visual stimulus was able to bias auditory localization in these experiments was directly related to its intrinsic ambiguity. This interpretation is also consistent with previous studies (Carrasco et al., 1995; Carrasco & Frieder, 1997; Rovamo & Raninen, 1990; Ransom-Hogg & Spillman, 1980; Virsu & Rovamo, 1979), demonstrating greater performance in terms of detection, accuracy, and speed to central rather than peripheral visual stimuli (i.e., ''M-scaling,'' Carrasco & Frieder, 1997). Indeed, central visual stimuli have lower susceptibility to auditory-induced visual illusions (Shams, Allman, & Shimojo, 2001; Thompson, Shams, Kamitani, & Shimojo, 2001). Localization bias was also directly correlated with the perception that the visual and auditory stimuli were ''unified'' and, thus, originated from the same location (see also Bertelson & Radeau, 1981). Thus, perceptions of unity were highest when the stimuli were centrally located. Although these results suggest a coupling of localization performance and perception of unity, it is not clear whether they reflect the same underlying neural mechanisms.

Despite the consistency of these observations across paradigms, performance proved to be highly variable between subjects. The source of this intersubject variability is not immediately clear. Since none of the individuals showed any consistent change in their responses across sessions, these differences are not easily explained by differences in learning. It is possible that the differences reflect differences in modality ''dominance.'' Visually dominant subjects might have a greater ability to locate a visual target (the primary factor that determined cross-modal bias here), and as a consequence, be more susceptible to visual–auditory bias. Subjects have been shown to vary in their sensory dominance, a variation that is directly related to their performance on visual–auditory multisensory tasks (see Giard & Peronet, 1999). However, it remains to be determined whether this factor plays any role in visual–auditory bias.

METHODS

Subjects

Five different subjects were used for each of the four (1a, 1b, 2, 3) experiments. Subjects in Experiments 1a, 2, and 3 were male and female undergraduate students between 19 and 23 years old, while subjects in Experiment 1b were male and female graduate students between 23 and 30 years old. All were naïve to the experimental aims, reported having normal or corrected-to-normal vision (contact lenses only) and normal hearing. All subjects provided full prior consent, which was approved by the Wake Forest University Institutional Review Board.

Apparatus

The apparatus (Figure 6A) consisted of a 110-cm (radius) perimetry containing an array of red light-emitting diodes (LEDs) and speakers. A primary set of 73 LEDs was separated by 2.5° of visual angle, and 17 speakers were separated by 10°. These LEDs were at eye level, and the speakers were centered 1.3 cm above eye level. An additional set of ''fixation'' LEDs were aligned with each of the speakers (4.5 cm below the target/biasing LEDs, with the space between them covered with a strip of black cardboard). An adjustable chin mount was positioned at the center of the perimetry, allowing a constant perspective across subjects and sessions. Inset 5 cm from the center of the semicircle was a joystick style yoke comprised of handles, two buttons, and a laser pointer. The beam of the pointer fell on the black cardboard strip when either button was

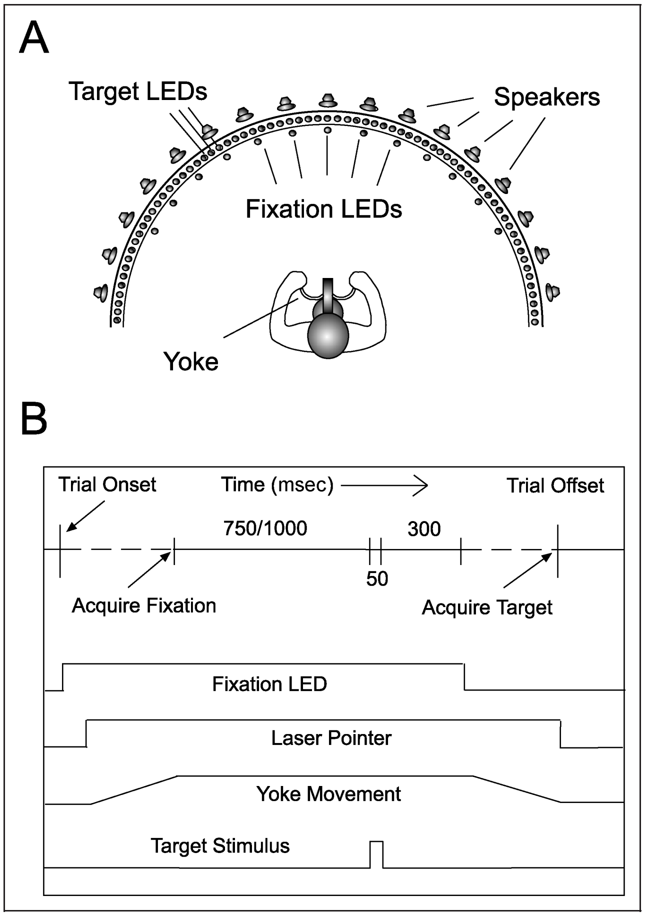

Figure 6. The experimental apparatus (A) and sequence of events during a single trial (B). See text for additional details.

pressed, and could be rotated horizontally by turning the yoke. This apparatus was used to perform localization judgments (see below). Below the table was a footswitch, used by the subjects to report spatial unity (see below). The entire apparatus was enclosed in a dark, sound-attenuated room.

The experiment was controlled from an adjoining room via a Pentium class personal computer utilizing a multifunction card from National Instruments (NI-DAQ PCI-6025E Digital/Analog I/O). The multifunction card interfaced with a customized switch box to allow the investigator to control LED and speaker intensities and onset/offset times. The card and box also received input from the yoke, buttons, and footswitch. Software interfacing with the box allowed the investigator to control all LEDs, speakers, and their combinations.

Stimuli

Stimuli consisted of illumination of an LED (660 nm λ at 0.003 ft cd) and broadband noise bursts delivered from a speaker. Noise bursts were presented at 64.4 dB SPL (A scale) measured from the chin mount at the center of the apparatus, and consisted of bandpass filtered tones ranging in frequency from 20 Hz to 10 kHz presented simultaneously in a square wave pattern. A Gold Line PWN1 White Noise Generator mounted above the subject's head maintained a constant background noise level of approximately 39 dB SPL (A scale). The duration of both the visual and auditory stimuli was 50 msec, and when both were presented they were simultaneous.

The position of the fixation LED varied randomly from trial to trial at 0°, ±10°, and ±20° from the center of the apparatus. Subjects were instructed to reorient their head and body to this fixation point at the beginning of each trial. The location of the fixation LED is referenced as midline, with target locations based on this framework. The fixation location varied to prevent subjects from learning the locations of the speakers, as well as to minimize the potential effects of minor variations in the absolute intensity of the speakers or LEDs. By convention, negative values referenced locations left of fixation, and positive values referenced locations to the right of fixation.

Procedure

Subjects dark-adapted for 10 min prior to beginning each block of trials. An illustration of the sequence of events from one trial is illustrated in Figure 6B. At the onset of a trial, one of the five fixation LEDs was illuminated. This signaled the subject to activate the laser pointer by pressing the button and aligning the laser beam just above the fixation LED. The experimental protocol required the subject to maintain this alignment within a ±1° margin for the duration of the fixation LED; otherwise, the trial was aborted. A stimulus, consisting of a 50-msec visual, auditory, or visual–auditory combination, was then presented either 750 or 1000 msec after fixation was achieved. The fixation LED remained illuminated throughout the stimulus presentation and for an additional 300 msec after termination of the stimulus. The offset of the fixation LED signaled the subject to move the laser pointer to the perceived location of the target. Once the perceived location of the target was acquired, the subject released the button, which turned off the laser and signaled the computer to record the final position of the pointer. This is the localization judgment, and marked the end of the trial in Experiments 1a and 1b. In Experiments 2 and 3, subjects were given an additional 1500 msec to press a footswitch to report whether or not they detected spatial unity between the sound and light during the trial. Subjects were allowed to pause between trials.

Experiment 1a

During Experiment 1a, subjects were instructed to localize a target auditory stimulus during the concurrent presentation of an irrelevant visual signal that was spatially disparate by a variable amount. The "location" of a target stimulus was referenced to the location of the auditory stimulus relative to the fixation point for that trial. Light/sound stimulus pairs, as well as a set of auditory-alone trials, were presented with the auditory target at 0°, ±10°, and ±30° from midline (fixation).

Subjects were told that a visual signal may occur, and that it may or may not coincide with the auditory target, but were not told of its relevance to their task; but rather that the auditory stimulus was always the target. "Multisensory" stimuli consisted of visual–auditory stimulus pairs that were spatially disparate by 0° (i.e., nondisparate), ±2.5°, ±5°, ±7.5°, ±10°, ±15°, or ±20°. By convention, negative disparities refer to visual stimuli central to the auditory stimulus and positive disparities refer to visual stimuli peripheral to the auditory stimulus. The auditory stimulus-alone (control) condition and 14 different stimuli per location produced a total of 70 stimulus combinations. Each stimulus combination was repeated three times per session in random succession for two sessions per day, for 5 days, yielding a total of 30 repetitions/stimulus combination/subject.

Experiment 1b

Experiment 1b was designed to obtain baseline performance values for localizing a visual, auditory, or spatially coincident visual/auditory stimulus. While in Experiment 1a the auditory stimulus was the target, in this experiment subjects were instructed to localize the stimulus, regardless of its modality. An auditory stimulus alone, visual stimulus alone, or spatially aligned visual–auditory stimulus was presented 0°, ±10°, ±20°, or ±40° from midline.

Experiment 2

Experiment 2 was identical to Experiment 1a, except that in addition to making a localization judgment, subjects reported whether or not the visual and auditory stimuli originated from the same location. After releasing the button controlling the laser pointer (thus completing the localization judgment), they were allowed 1500 msec to press a pedal below their preferred foot. For the first five sessions, pressing the footswitch indicated that the two stimuli were in the same place, while during the remaining five sessions this rule changed, so that pressing the switch indicated that the signals were not spatially coincident. The purpose of this task was twofold: to make subjects actively aware of the potential spatial disparity between the two stimuli, and to determine the relationship between localization bias and the perception of cross-modal spatial ''unity.''

Experiment 3

In Experiment 3, subjects reported whether the visual and auditory stimuli originated from the same place (as in Experiment 2), but they did not make a localization judgment (as in Experiment 1a). They continued to use the laser pointer to locate the fixation LED and to initiate the trial and stimulus presentation, but then did not move it to locate the auditory stimulus. As in Experiment 2, they were allowed 1500 msec to press the footswitch after releasing the laser pointer button. Also as in Experiment 2, responses were balanced by switching the pedal ''rule'' after five sessions. The purpose of this experiment was to ensure that making a localization judgment prior to reporting spatial alignment of the signals does not dramatically influence the spatial ''unity'' report. All stimulus combinations were identical to Experiments 1a and 2.

Data Analysis

To assess bias from a disparate cross-modal signal, responses were adjusted relative to performance with a nondisparate (i.e., spatially coincident) multisensory presentation. For each random repetition of the stimulus series within a given session, each subject's error ''without'' multisensory disparity was determined and subtracted from the amount of error when a disparity was introduced. This correction was applied to each experimental session, target position in space, and to each subject. These normalized data represent the amount of error introduced by separating the stimuli by a specific amount of space while accounting for individual patterns of undershooting or overshooting, as well as normal variation over time.

''Percent'' bias was calculated by dividing the (corrected) amount of error, expressed in degrees, by the amount of spatial disparity between the visual and auditory signals, for every trial. This metric represents the percentage of ''pull'' that the visual signal had over the auditory target. Thus, a score of 100% represents complete bias, where the subject pointed directly at the visual stimulus. Positive scores less than 100% indicate judgments that fell between the two stimuli; a score greater than 100% represents a response beyond the location of the visual stimulus (i.e., an overshoot). Note that bias is not computed when there is no disparity. A pictorial example of bias is shown in Figure 7.

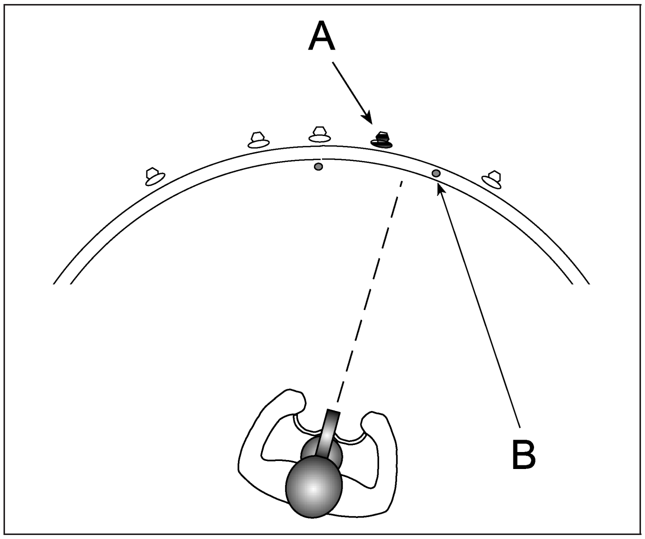

Figure 7. An example of visual bias of auditory target localization. Bias represents localization error as a percentage of the distance between the target speaker (A) and an LED light (B). In this example, fixation is at 0°, the auditory target location is at 10°, and the visual stimulus is at 20°. The subject pointed to 15°, representing a bias of 50%.

An unfortunate mathematical artifact of this process is an exaggeration of the distribution of responses for small-disparity conditions. For example, a small error of 5° when there is a 2.5° disparity produces a bias score of 200%. Yet, the same percent bias score would require a 30° error when there is a 15° disparity between the stimuli. Because the mean of the distribution is unaffected by this distortion, it is still appropriate to analyze the average bias per condition. However, the inequality in response distributions makes it inappropriate to use parametric statistics to compare bias within individuals under differing amounts of disparity. Currently, we do not have an appropriate measure for correcting this problem, so all tests for the significance of bias under differing amounts of disparity are based upon a single-sample comparison to zero.

During Experiments 2 and 3, subjects reported whether they perceived the visual and auditory stimuli as originating from the same location. For each spatial disparity and position, the number of times each subject reported multisensory unity was divided by the total number of trials ($n = 30$). This produced a percentage of times that "unity" was reported. Notice that this computation does not produce a variance term for an individual subject.

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Note

1. Note than subject KC from Experiment 2 displays variability that is far greater than the average, and KC's best average scores exceed those obtained in the group when localizing the auditory target alone in Experiment 1b. Those data were excluded from further analysis.

REFERENCES

Bermant, R. I., & Welch, R. B. (1976). Effect of degree of separation of visual–auditory stimulus and eye position upon spatial interaction of vision and audition. *Perceptual and Motor Skills, 43,* 487–493.

Bertelson, P., & Aschersleben, G. (1998). Automatic visual bias of perceived auditory location. *Psychonomic Bulletin and Review, 5,* 482–489.

Bertelson, P., & Radeau, M. (1981). Cross-modal bias and perceptual fusion with auditory–visual spatial discordance. *Perception and Psychophysics, 29,* 578–584.

Brindley, G. S., & Lewin, W. S. (1968). The sensations produced by electrical stimulation of the visual cortex. *Journal of Physiology, 196,* 479–493.

Carrasco, M., Evert, D. L., Chang, I., & Katz, S. M. (1995). The eccentricity effect: Target eccentricity affects performance on conjunction searches. *Perception and Psychophysics, 57,* 1241–1261.

Carrasco, M., & Frieder, K. S. (1997). Cortical magnification neutralizes the eccentricity effect in visual search. *Vision Research, 37,* 63–82.

Choe, C. S., Welch, R. B., Guilford, R. M., & Juola, J. (1975). The "ventriloquist effect": Visual dominance or response bias? *Perception and Psychophysics, 18,* 55–60.

Giard, M. H., & Peronet, F. (1999). Auditory–visual integration during multimodal object recognition in humans: A behavioral and electrophysiological study. *Journal of Cognitive Neuroscience, 11,* 473–490.

Hairston, W. D., Vaughan, W. J., Wallace, M. T., Stein, B. E., & Schirillo, J. A. (2001). Cross-modal bias is related to variability in visual localization. *Society for Neuroscience Abstracts, 27,* 1342.

Howard, I. P., & Templeton, W. B. (1966). *Human spatial orientation.* New York: Wiley.

Jack, C. E., & Thurlow, W. R. (1973). Effects of degree of visual association and angle of displacement on the "ventriloquism" effect. *Perceptual and Motor Skills, 37,* 967–979.

Lewald, J., Ehrenstein, W. H., & Guski, R. (2001). Spatio-temporal constraints for auditory–visual integration. *Behavioural Brain Research, 121,* 69–79.

Mateeff, S., & Gourevich, A. (1983). Peripheral vision and perceived visual direction. *Biological Cybernetics, 49,* 111–118.

Radeau, M. (1985). Signal intensity, task context, and auditory–visual interactions. *Perception, 14,* 571–577.

Radeau, M., & Bertelson, P. (1987). Auditory–visual interaction and the timing of inputs. *Psychological Research, 49,* 17–22.

Ransom-Hogg, A., & Spillman, L. (1980). Perceptive fields in fovea and periphery of the light and dark-adapted retina. *Vision Research, 20,* 221–228.

Roberson, G., Hairston, W., Vaughan, J., Wallace, M., Stein, B., Laurienti, P., & Schirillo, J. (2001). Integrating multisensory signals across time and space. *Society for Neuroscience Abstracts, 27,* 1342.

Rovamo, J., & Raninen, A. (1990). Cortical acuity and the luminous flux collected by retinal ganglion cells at various eccentricities in human rod and cone vision. *Vision Research, 30,* 11–21.

Shams, L. B., Allman, J., & Shimojo, S. (2001). Illusory visual motion induced by sound. *Society for Neuroscience Abstracts, 27,* 1340.

Slutsky, D. A., & Recanzone, G. H. (2001). Temporal and spatial dependency of the ventriloquism effect. *NeuroReport, 12,* 7–10.

Thompson, S. E., Shams, L. B., Kamitani, Y., & Shimojo, S. (2001). Brain mechanisms underlying a sound-induced visual illusion. *Society for Neuroscience Abstracts, 27,* 1342.

Thurlow, W. R., & Jack, C. E. (1973). Certain determinants of the ventriloquism effect. *Perceptual and Motor Skills, 36,* 1171–1184.

Thurlow, W. R., & Rosenthal, T. M. (1976). Further study of existence regions for the "ventriloquism effect". *Journal of the American Audiology Society, 1,* 280–286.

Virsu, V., & Rovamo, J. (1979). Visual resolution, contrast sensitivity, and the cortical magnification factor. *Experimental Brain Research, 37,* 475–494.

Warren, D. H. (1979). Spatial localization under conflict conditions: Is there a single explanation? *Perception, 8,* 323–337.

Weerts, T. C., & Thurlow, W. R. (1971). The effects of eye position and expectation on sound localization. *Perception and Psychophysics, 9,* 35–39.

Welch, R. B. (1972). The effect of experienced limb identity upon adaptation to simulated displacement of the visual field. *Perception and Psychophysics, 12,* 453–456.

Welch, R. B., & Warren, D. H. (1986). Intersensory interactions. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance,* vol. 1, *Sensory processes and perception* (pp. 1–36). New York: Wiley.