Use of sound-pressure level in auditory distance discrimination by 6-month-old infants and adults

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Six-month-old infants have been found to respond differentially to sounding objects placed within reach and beyond reach when no visual cues were available. The goal of the present study was to investigate whether sound-pressure level (SPL) serves as an auditory cue in distance discrimination. Thirty-two 6-month-olds were presented with recordings of sounding objects first in the light at midline position, then in the dark at 45° to the right and left. On half of the dark trials the object was near (15 cm), and on half it was far (100 cm). For the control group the near sound was naturally 7 dB louder than the far. The experimental group had SPL counterbalanced across near and far locations to provide an inconsistent cue. Measures of infant reaching were scored from videotape. Two groups of adults were run under similar conditions; adults were tested on reaching as well as verbal reports of distance judgment. All infants reached more for the near object, regardless of the sound's SPL, suggesting that infants did not rely on this as a major distance cue. In contrast, adults' verbal judgments of distance were based heavily on SPL, a strategy that produced higher error rates in the group with SPL counterbalanced across distance. A followup study in which adults were instructed to move their heads before judging the sound's distance did not support the hypothesis that infants' head movements were responsible for their overcoming the misleading SPL information.

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INTRODUCTION

Depth perception in infants has been studied extensively over the last two decades, yielding a great deal of literature about its development in the visual modality (Yonas and Granrud, 1985). In contrast, relatively little is known about infants' auditory depth perception, perhaps because this ability is still not well understood in adults. In a recent investigation Clifton *et al.* (1991) found that by 6 months of age infants discriminated between sounding objects presented either within reach or beyond reach when no visual cues were available. They tested infants with either a live rattle sound, or a computer-generated, tape-recorded sound. The objects were presented in complete darkness at 30° left and right, within (15 cm away) and beyond (60 cm away) reach. Infants' ability to localize the sound was assessed by their reaching into a target zone designated by the position of the object when it was within reach. Infants reached more frequently into the target zone when the object could be contacted than when it was beyond reach. This study was the first of its kind to demonstrate that by 6 months infants dichotomize auditory space into at least two areas in relation to the body: within reach and beyond reach.

The distance between the within and beyond conditions in the Clifton *et al.* (1991) investigation was 45 cm, which resulted in a natural sound-pressure level (SPL) difference of 6 dB. By the age of 7 months infants can discriminate SPL differences as small as 3 dB (Bull *et al.*, 1984; Sinnott and Aslin, 1985), suggesting that SPL could have served as a depth cue in this situation. Clifton *et al.* (1991) allowed distance cues to vary naturally as the sounding objects were presented near and far away from the infant without changing the level of the sound source. Although SPL differences were likely to be used in discriminating distance, other cues were confounded by this procedure. The present study manipulated SPL in order to investigate whether infants utilize this as a major cue in distance perception.

Sound-pressure level has been the most widely studied depth cue in adult listeners since the turn of the century (Edwards, 1955; Gamble, 1909). We refer to it as sound-pressure level, though it is more commonly, albeit incorrectly, called intensity (see Ashmead *et al.*, 1990; Kuhn, 1977). As a sound source advances toward or retreats from a listener, the SPL varies as an inverse function of the distance from the source (Coleman, 1962); for every doubling of distance there is a drop of 6 dB in SPL (Blauert, 1983, p. 28f; Mershon and King, 1975). Perceptually, as the loudness of sound at the ear decreases, the listeners' judgment of the apparent distance at the ear increases (Gardner, 1969; von Bekesy, 1949).

A number of additional cues may be involved in adults' perception of auditory distance, depending on the listener's distance from the sound source (for review, see Blauert, 1983, pp. 116–131; Coleman, 1963). At long distances beyond 15 m, high frequencies become attenuated moreso than low frequencies because they are absorbed more readily in the air, resulting in depth information based on the spectral content of the auditory stimulus. In addition, pulsating sound sources generate spherical waves around the listener's head, which decrease in curvature with distance, and whose shape serves as a cue especially at long distances. At short distances below 3 m, depth cues are derived from the curvature of sound wave fronts arriving at the head, as well as changes in the spectral content of the sound (Blauert, 1983, pp. 73–75, 118). The application of certain cues at short distances depends also on characteristics of the sound source (Coleman, 1968), familiarity of the listener with the sound (Coleman, 1962), the auditory environment (Mershon and Bowers, 1979; Mershon and King, 1975) the listener's task (Ashmead *et al.*, 1990), and contribution by the listener's motion (Ashmead and LeRoy, 1992).

Several investigations have measured relative-distance discrimination thresholds by asking adult listeners to report when they detected a change in the distance of a sound. The basic finding has been an increase in threshold with decreased distance, measured by the percentage of change in distance that can be detected (Simpson and Stanton, 1973; Strybel and Perrott, 1984). Recently Ashmead *et al.* (1990) showed that distance thresholds are subject to response biases that can be significantly reduced by using a forced-choice methodology in which subjects judged whether or not they detected a change in distance. This latter finding is furthermore restricted to the availability of SPL cues. This study as well as others reported that although SPL may not be the only cue for auditory depth perception, adults do tend to rely on it heavily.

In the present study,we investigated whether infants could utilize a change in SPL as a depth cue. Six-month-old infants and adults were presented with sounding objects in the dark, half of the subjects at each age with distance cues consistent with SPL and half with inconsistent SPL. If subjects relied on SPL as a major depth cue, the experimental groups receiving inconsistent SPL information would be wrong half of the time because they would respond as if the louder sounding objects were near and the softer sounding objects were more distant. However, if SPL was not the dominant cue, experimental subjects would base their judgment on other distance cues in order to solve the problem. Control subjects who received consistent SPL information were expected to respond correctly because all distance cues worked together in their situation.

I. METHOD

A. Subjects

Infants were recruited from published birth announcements in the newspapers by letter and a followup telephone call. The final sample consisted of 32 infants (21 male, 11 female; mean age $= 27.8 \pm 1.7$ weeks; age range = 24–30 weeks), all of whom met the following criteria: (1) birth at full term; (2) no history of frequent ear infections or suspicion of hearing impairment; (3) no suspicion of a cold and no medication taken on test date. Infants were assigned randomly to two groups, with $N = 16$ in each group. An additional group of 14 infants tested were not included in the final sample due to fussiness (11), ear infection on the day of testing (2) and no reaching in the light (1).

The adult group consisted of 40 subjects (23 male, 17 female; mean age $= 21 \pm 3$ years; range = 18–37 years), all of whom had normal hearing according to self-report. Two additional subjects were excluded from the final sample due to experimental error.

B. Stimulus

The stimulus was a tape recording of 4 jingle bells shaken continuously and rapidly at a rate of 3/s. The sound was amplified (Onkyo A-8170), and played through one of three loudspeakers (Realistic 40-1325) in the testing room. An octave-band spectrum analysis was performed with a Bruel & Kjaer sound level meter (type 2204) placed at the listener's head position. The sound was broadband, with significant energy [63–74 dB(A)] concentrated at 2 kHz and higher, with no fall off at 16 kHz, the highest frequency measured (see Table I). The stimulus was presented at two distances in relation to the infant's head: near (15 cm away) and far (100 cm away). Sound was produced at one of two SPLs, averaging 74 and 67 dB(A) as measured at the approximate location of the infant's head. This 7-dB difference was the natural falloff in SPL at the far versus the near position, based on direct measurement; this difference is less than what would be expected in an anechoic environment, indicating that the room was somewhat reverberant. A 7-dB difference can be discriminated easily by infants at this age (Bull *et al.*, 1984; Sinnott and Aslin, 1985).

C. Apparatus

The experiment was conducted in a 3.5×4 m sound deadened, double-walled room (background level 29 dB(A), adjoining a control room. Three small directional loudspeakers, positioned at shoulder height for infants and midtorso height for adults, could each be slid toward and away from the subject at midline, and 45° to the right and left. When pulled all the way back, the loudspeakers were concealed behind a curtain enclosure. A small colorful finger puppet ($7.5\ \text{cm} \times 4.5 \times 3.5$ cm plastic replica of Big Bird) was attached with velcro to each loudspeaker, and could easily be grasped and removed in order to make the sounding object more attractive to the infants.

Ambient illumination was low, so that the loudspeakers and finger puppets were not visible through the curtain. An infra-red light source was mounted overhead to permit recording in the dark. Two infrared sensitive video cameras (Panasonic-WV 1850) monitored the subject's behaviors. One camera was positioned directly above the infant, provid-

TABLE I. Octave-band spectrum analysis.

	Octave-band level in dB SPL	
Frequency (Hz)	Bell tape	Ambient noise
31.5	54	54
63	56	45
125	38	37
250	34	32
500	34	< 30
1000	51	< 30
2000	63	< 30
4000	68	< 30
8000	74	< 30
16000	69	< 30

Overall level: 74 dB(A)

ing a "bird's eye" view of head and arm movements. This image was relayed through a date/timer (FOR-A model VTG-33), to a video recorder (Panasonic VHS model NV-8950), such that every frame was labeled with time in hundredths of a second. A second camera was positioned to the left of the subject behind a dark curtain to provide a side view, which was recorded on a second video deck. Opposite the camera to the infant's right was another dark curtain marked with a grid of black tape that facilitated the scoring of hand movements in the vertical plane. The camera images were displayed on separate monitors in the control room, to allow a full-screen view from both cameras.

D. Procedure

Infants sat on their parents' lap facing the apparatus. Parents were asked to refrain from talking and told to hold the infant at the hips in order to provide ample support while allowing free arm movement for reaching. Parents wore head phones that masked the direction and SPL of the sound.

One experimenter stood facing the infant at midline, directly behind the apparatus. A second experimenter in the control room regulated presentation of the auditory stimuli, and gave instructions to the inside experimenter over head phones. Each session began with four "warm-up" trials in the light at midline, which familiarized the infants with the sound at the near and far positions, as well as screened infants for their willingness to reach for the sounding object. Any infant who did not reach on at least 3/4 warm-up trials was eliminated from the final sample because subsequent failure to reach for sounding objects in the dark would be ambiguous. Each light trial began when the infant's head was centered at midline. A flap in the curtain was lifted, and the loudspeaker advanced to the far position, where the sound was played for 5 s at a level of 67 dB(A). The sound was subsequently turned off while the loudspeaker was advanced to the near position, and played at a level of 74 dB(A), until the infant contacted the object (toy or loudspeaker), or for 20 s, whichever came first. If the infant did not contact the toy, the experimenter removed the toy and handed it to the infant to familiarize and demonstrate the apparatus to the infant.

On dark trials, the experimenter pressed a foot switch that turned off the room lights and turned on the infrared light. She then received instructions concerning the position (near versus far) and side (right versus left) of the loudspeaker for the next trial, in order to prevent possible cuing to the infant in the light. The experimenter advanced the loudspeaker to the appropriate position, aided by instructions from the observer who could see the image on the video monitor. Movement of the loudspeakers produced a soft sound at a fixed point on the apparatus where the metal rod supporting the speakers slid through a joint. During near trials the object had to be advanced further away from its pretrial resting position, a longer movement than when it was advanced to the far position. To prevent possible distance cues based on this difference, the loudspeaker was always positioned with two movements: the first advanced it halfway between the near and far positions, and the second retracted it back to the far position or advanced it forward to the near position. Pilot testing with adults showed that they could not reliably determine the distance of the loudspeakers based on the sound produced by moving them into position.

The observer timed each trial and signaled the experimenter to end the trial after 20 s. On near trials if the infant contacted the object, the lights were turned on while the loudspeaker was still in the near position, and if the infant had not removed the toy, the investigator did so and handed it to the infant. On far trials, once 20 s had passed, the loudspeaker was withdrawn before the lights were turned on. During intertrial intervals the lights were on in order to prevent possible distress produced by long periods in the dark. If the infant became fussy during testing ($N = 11$), a short break was taken. If testing resumed, in order to remind the infant of the task an additional light trial was introduced regardless of where the testing had ceased. If the infant continued to fuss, the session was terminated. All infants in the sample completed the session. At the end of the visit infants received a certificate of appreciation and a picture book.

Adults received the trial sequence twice. Once they verbally judged whether the speaker was in the near or far position, and once they reached for the sounding object in the dark. On the reaching task subjects were instructed to make one reach on each trial and attempt to land their hand on top of the object. Note that adults were not asked to refrain from reaching when they thought the object was out of reach, so their reaching behavior does not reflect their judgment of near versus far. Subjects were told that they might contact the object on some but not all trials, and that if no contact was made on the first attempt they should not try again. Procedure for testing adults on the reaching sequence was similar to that of infants. If contact was made during near trials, the lights were turned on, and if no contact was made, the object was withdrawn before the lights were turned back on. During the verbal sequence no feedback was given on either near or far trials. Adults were also instructed to keep their head centered during stimulus presentation, sit upright in their chairs and keep their head still.

E. Design

1. Infants

Each infant received 4 initial trials in the light(L), followed by 8 trials inthe dark (D) with 3 additional light trials interspersed to maintain the infant's interest in the task. Trials were always presented in the following sequence: L-L-L-L-D-D-L-D-D-L-D-D-L-D-D. In the dark each infant received two trials at each of four positions (near right; near left; far right; far left). Infants in the control group were presented with the sound at its greater SPL [74 dB(A)] in the near positions and at the lesser SPL [67 dB(A)] in the far positions; that is, the sound level dropped with greater distance as it would naturally. The experimental group received both levels at each of the four positions; they had essentially eight different trial types {near right [67 dB(A)]; near right [74 dB(A)]; near left [67 dB(A)]; near left [74 dB(A)]; far right [67 dB(A)]; far right [74 dB(A)]; far left [67 dB(A)]; far left [74 dB(A)]}. The order of trial type for the eight dark trials was completely randomized for each subject.

2. Adults

Experimental and control adult groups received the same trial types as those of infants, once with verbal judgment and once with instructions to reach. There were 20 adults in each condition, and within each condition subjects were randomly divided into 2 groups of 10 with order counterbalanced for reaching-verbal instructions. The R-V groups were asked to reach for the objects during the first sequence, and verbally judge the position of the objects for the second sequence. The V-R groups had the order of tasks reversed. The purpose of the reaching task was to see whether judgments on the verbal task would be facilitated for subjects who were presented with the reaching task first, and to compare accuracy of reaching on near trials with the infants.

F. Data scoring

1. Infants

The scoring system used here was modeled after Clifton *et al.* (1991), which can be consulted for additional detail. The overhead view of the infant was used for scoring hand positions in the x–y plane, and the side view was used for determining vertical positions. A computer scoring system employed a "mouse" to mark the locations of both hands and the object. A scoring setup described by Page *et al.* (1989) allowed the reflection from the video monitor to be superimposed upon the screen from the computer monitor. To achieve this, the video monitor displaying the overhead image was positioned at a 90° angle to a computer monitor with a piece of plexiglass bisecting the angle. A scorer looked at the video reflection on the computer screen and moved a "mouse" to the positions to be scored. The position of the object was scored at the point where the toy was attached to the loudspeaker. Each trial was scored beginning at 1 s prior to sound onset through the end of the trial, using frozen frames advanced every 0.5 s (determined by the date/time readings to the nearest 0.01 s). The x–y coordinates for each position were stored by the computer, and used to compute the position of the hands in relation to the object.

Reaching space was defined as an arc of 65 deg on either side of midline in front of the infant, which measured 37 cm at the object's near position. A target area was designated on the right or left, representing 10 cm in the horizontal plane, 9 cm in the vertical and 12 cm in depth, occupied by the loudspeaker plus the attached toy. For each infant, x–y coordinates for the target areas of the two near trials on the same side were averaged to yield one final target area, which was used to specify a target reach on both near and far trials for that side. The same target region was used to score reaching on both near and far trials. Reaches into the target area, not contacts with the object were scored, because there could be no contact when the object was beyond reach.

All trials were initially scored using the computer coordinates, to determine if either hand entered the target area on the x–y plane. Reliability between two independent observers was calculated on 35% of the data, and yielded agreement on 95% of the trials. All hand movements identified by the computer as being within the target area were subsequently viewed on the overhead video image, to determine whether those movements were reaches. A reach was defined as the extension of a hand away from the body in the direction of the apparatus. If a hand entered the target area as part of a swipe of the arm, flapping of the arm, or torso movement it was not considered a reach. Movements were scored by independent observers, who agreed on 97% of the trials. Discrepancies were resolved by another independent observer. All behaviors defined as reaches into the x–y planes were subsequently viewed on the sideview video image to determine whether they also entered the target area at the correct height of the object in the z plane. Finally, the videotapes were viewed to identify extensions of the hands into the apparatus space outside the computer-designated target areas to determine how many reaches would be classified as errors.

Movements classified as reaches were assigned to one of six categories.

(1) Target zone reaches: Reaches into the target zone on the side where the sound was being presented. For near trials these reaches were "correct," whereas for far trials they were "false alarms" since the sounding object was not actually in that space at the time.

(2) Height errors: Reaches into the correct target zone on the side where the sound was being presented, but only in the x–y planes, not in the z plane, so that the hand was above or below the target space.

(3) Nontarget errors: Reaches to nontarget areas, defined as the target area on the opposite side of the apparatus from that on which the sound was presented, i.e., the side which did not contain the object on that trial.

(4) Nontarget height errors: Reaches that were above or below the nontarget area.

(5) Hemifield errors: Trials in which the hands did not enter the target zones on either side were dichotomized into reaches in the target's hemifield area and nontarget hemifield.

(6) Center errors: Reaches into the center zone when the sounding object was presented either to the right or left. These reaches were infrequent, but were nonetheless classified separately in order to demonstrate that in the dark the infants were not merely reaching in the center, where they had actually seen and reached for the object during light trials.

Our scoring permitted an infant to have more than one type of reach on each trial. For instance, if the hands entered the target and nontarget areas on the same trial, an infant would have both a correct reach and a nontarget error.

2. Adults

Verbal judgments for adults were classified as correct when the judgment coincided with the object's position and incorrect when it did not. Reaching behaviors for adults were scored for contacts on near trials to obtain a rough estimate of how accurately adults could judge the sound's location with a single attempt.

II. RESULTS

A. Infants

Infant reaching was analyzed separately for light and dark trials. Contact with the object occurred on 97% of light trials, indicating that when visible and within reach, the objects were easily obtained. Infants reached less in the dark compared with the light (75% on near trials; 36% of far trials), but 31 of the 32 infants reached in the dark on at least one trial.

Reaching in the dark was first analyzed to establish whether infants generally reached more often when the object was presented within reach (near) or at the same angle of orientation, beyond reach (far). The percentage of near and far trials on which infants reached in the dark, whether or not their hand entered the target area, is plotted for control and experimental infants in Fig. 1. A 2-way ANOVA conducted on group (control versus experimental) and distance (near versus far) yielded a significant effect of distance [$F(1,30) = 15.76$, $p < 0.001$], but there was no significant difference between groups ($p > 0.187$), and no interaction ($p > 0.05$). Infants reached more often when the sound was presented at the near position than when it was in the far position, regardless of whether distance cues were correlated with SPL.

While the preceding analysis of frequency indicated that infants reached more often when the object was near, reaching accuracy was not tested. One approach to this issue was to calculate the proportion of trials on which a hand entered the target zone on the very first reach out of the total number of trials containing a reach. The data, which are plotted in Fig. 2, were compared in a 2-way ANOVA of group (control versus experimental) and distance (near versus far). More target reaching was evident on near (80.5%) than on far (37.5%) trials [$F(1,30) = 20.86$, $p < 0.001$], again with no effect of group and no interaction. Infants were clearly utilizing auditory cues to guide their reaching, rather than merely entering the target zone by chance after numerous attempts. Furthermore, inconsistent SPL did not lower performance. Considering the proportion of trials when *at least one* target reach occurred at any time during the trial, we found more reaches on near (68%) than on far (50%) trials [$F(1,30) = 64.49$, $p < 0.001$], with no reliable group effect or interaction. This result is particularly impressive considering that the far trials always lasted 20 s compared to the near trials ($M = 11.8$ s, range = 1.02–20.0 s), because contact with the object could end a near trial. Thus, even when infants had more time to reach into the target zone on far trials, reaching was reduced relative to near trials.

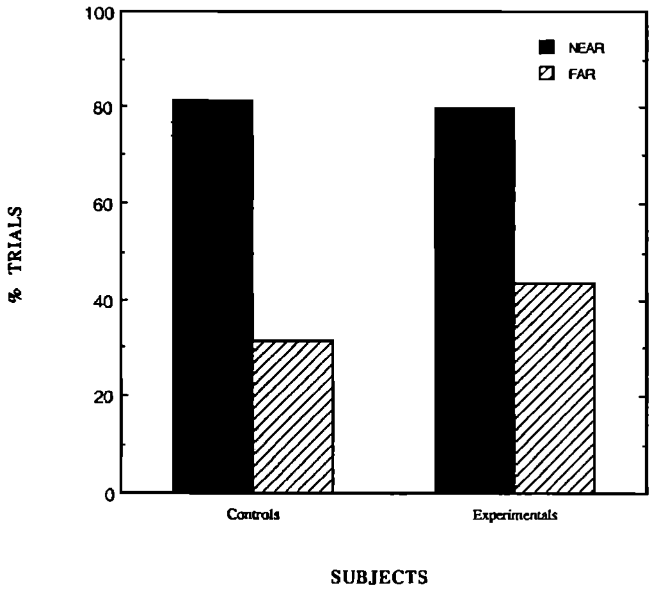

FIG. 2. Percentage of trials on which infants reached into the "target" zone on the first reach, out of the total number of reaching trials, plotted for control and experimental subjects at near and far positions.

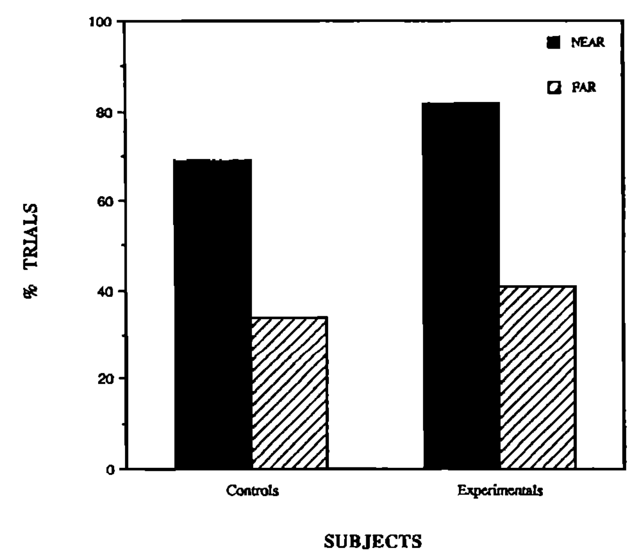

FIG. 1. Percentage of trials on which infants reached in the dark, out of the total number of trials, plotted for control and experimental subjects at near and far positions.

Reaching accuracy was further examined by comparing reaches outside the target area, which occurred on 32% of near and 50% of far trials. Each reach was assigned to a category defined in terms of the endpoint of the reach. The different types of reaching were not mutually exclusive for the same trial, so on any given trial an infant could produce numerous movements, each of which could contribute to a different category. The number of trials in each reaching-movement category plus a no-reach category are plotted in Fig. 3 for near and far trials. For near trials reaching behavior occurred most frequently in the target zone, and most far trials fell into the no-reach category. The number of trials in the various categories were compared in a 3-way ANOVA of group (control versus experimental), distance (near versus far) and movement type. Results yielded a significant effect of movement type [$F(3,93) = 13.71$, $p < 0.001$], and a significant interaction of movement type $\times$ distance

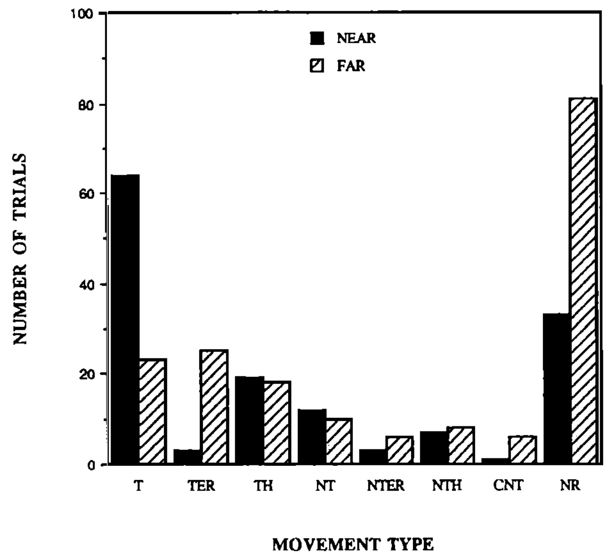

FIG. 3. The number of near and far trials on which infants reached into each area in the apparatus (T = target zone; TER = target height error; TH = target hemifield; NT = nontarget zone; NTER = nontarget height error; NTH = nontarget hemifield; CNT = center of apparatus; NR = no reach). Data are combined for control and experimental groups. Note that these categories are not mutually exclusive (except for NR), so a trial could have more than one movement type.

[$F(3,93) = 22.08, p < 0.001$], a marginal but nonsignificant effect of distance ($p < 0.06$), and no main effect of group $p > 0.56$.

Post-hoc t tests were conducted to delineate the source of interaction (with adjustments of p values for multiple comparisons requiring significance at $p < 0.002$), confirmed what is evident from Fig. 3. Follow-up tests of the distance $\times$ movement-type interaction indicated an effect of distance only in the target ($p < 0.001$) and target error ($p < 0.002$) reaches but not in the other two movements. On near trials the majority of reaches went into the target area, above and beyond all other types of reaches (p's < 0.0001). In contrast, on far trials infants were just as likely to produce target, target error or target hemifield reaches (p's > 0.05), indicating that they reached with much less accuracy and no clear demonstration of knowledge about the angular location of the object within the hemifield.

When reaching in the dark infants were not simply attempting to reach for the object where they may have encountered it on previous trials. Reaches into the opposite, or nontarget area, were significantly reduced relative to target area reaching. Out of the total number of near trials with reaching, 64 out of 94 (68%) had target reaches, compared with 12/94 (13%) with nontarget reaches. Similarly of the far trials with reaching, 23 out of 48 (48%) had target reaches, compared to 10/48 (21%) with nontarget reaches. Infants were not merely reaching for an unspecified target in the dark, but rather they utilized auditory cues to seek contact with a localizable stimulus.

A chief question of this study was whether SPL functions as a guiding cue to 6-month-old infants. This issue was indirectly addressed in earlier analyses, which found no difference between control and experimental infants in their frequency and accuracy of reaching on near and far trials. Depth was confounded with SPL for control infants, but data from experimental infants can be analyzed for these variables separately. If infants relied heavily on SPL, then the experimental group, who heard both levels at the two distances, should have reached more often for the louder sound, regardless of distance. The number of trials on which experimental infants reached into the target area were compared with a 2-way ANOVA of SPL (67 dB vs 74 dB) $\times$distance (near versus far). Experimental infants reached significantly more on near than far trials [$F(1,15) = 23.44$, $p < 0.001$], but there was no effect of SPL [$F(1,15) = 0.26$, $p > 0.62$] and no significant interaction ($p < 0.168$). These results suggest that in reaching for sounding objects in the dark, infants do not rely solely on the relative difference in SPL at the two positions in making the distance discrimination.

B. Adults—Experiment 1

1. Verbal reports

Adult data were not directly compared with those of infants since the response measures used to assess distance judgment were different for the two age groups. Two components of verbal judgments of distance were assessed for adults: (a) accuracy of the judgments on each trial and (b) tendencies to report "near" and "far" under given conditions. The percentage of trials with correct verbal judgments are plotted in Fig.4. These data were compared in a 3-way ANOVA of order (reaching-verbal vs verbal-reaching) $\times$group (control versus experimental) $\times$ distance (near versus far). There was no effect of order and no significant interactions, so data for the two groups were combined for all future analyses. The other two main effects in this analysis were significant. First, control subjects were correct on significantly more trials than experimental subjects [$F(1,36) = 20.75$, $p < 0.001$]. These results suggest that when making distance judgements, having consistent infor-

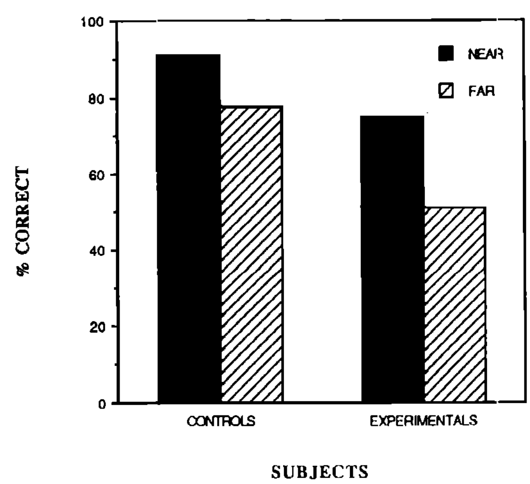

FIG. 4. Percent of trials on which adult subjects were correct in their verbal responses, plotted for control and experimental subjects, at both near and far positions.

mation about distance and SPL facilitated the control subjects' performance, whereas inconsistent distance and SPL information hindered the performance of experimental subjects. Second, subjects in both the control and experimental conditions were correct significantly more often on near than far trials [$F(1,36) = 20.15, p < 0.001$], which reflects a greater tendency to report "near" than "far."

If adults were more likely to be correct when the SPL of a sound correlated with its distance, the next question was whether they actually relied on it as the major cue in making their judgments. If so, then listeners in the experimental condition should have judged louder sounds as "near" and softer sounds as "far" without regard for the actual position of the object. The percentage of trials on which experimental subjects reported "near" and "far" is plotted for the two levels in Fig. 5, with distance pooled at each SPL. On the louder trials (74 dB) subjects reported "near" more frequently than they did "far" [$t(19) = 10.47$, $p < 0.001$], whereas on the softer trials (67 dB) they reported "far" more often than "near" [$t(19) = 3.32, p < 0.004$]. This tendency to weigh SPL heavily is further reflected in the level of accuracy at different intensities. The number of trials on which experimental subjects' responses were correct was compared in a 2-way ANOVA of distance (near versus far) and SPL (67 dB vs 74 dB), revealing a significant effect of distance [$F(1,19) = 11.47, p < 0.003$], and a significant distance $\times$ SPL interaction [$F(1,19) = 56.24, p < 0.001$], but no main effect of SPL ($p > 0.51$). Results of *post-hoc t* tests (adjustments for multiple comparisons requiring significance at $p < 0.008$) indicated that subjects were more likely to be correct on the louder SPL if the object was in the near rather than the far position [$t(19) = 4.50$, $p < 0.001$], but the reverse was true for the softer SPL, where correct answers were obtained more often at the far position than at the near position [$t(19) = -2.94, p < 0.008$].

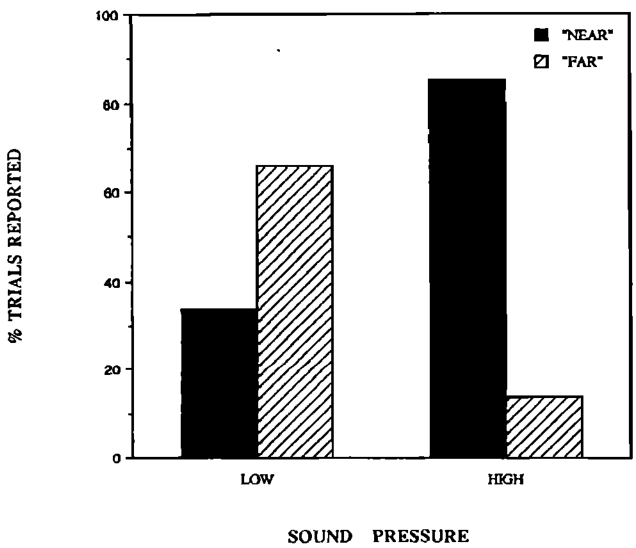

FIG. 5. Percent of trials on which experimental adults reported that the sound was "near" or "far," plotted for two intensities (low and high). For experimental subjects trials are added over near and far positions at each intensity level.

2. Reaching

Adults' reaching behavior was assessed for near trials and scored as "correct" if contact with the object was made, which indicated that their hand had entered the target zone area scored for the infant data. The aim of this assessment was to establish whether adults were capable of localizing the sounding objects in a manner that we required infants to use, and to compare adults' accuracy with that of the infants. Only the first reach in the dark was considered for infants, in order to compare with adults who were instructed to reach only once on each trial. The proportions of trials on which the hands entered the target zone were compared in a 2-way ANOVA of age (adults versus infants) $\times$ group (controls vs experimentals). Mean percent correct for infants (80.47%) was not significantly different from adults (85%), nor was there a group difference. Infants were as accurate as adults on their first attempt to contact a sounding object in the dark within reach, and all subjects were able to contact the object regardless of whether distance and SPL were correlated. The latter finding is especially interesting for adults who demonstrated a significant increase in verbal judgment errors when SPL was randomized across distance. Adults made mistakes in verbal judgments on 5% of near-loud trials compared with 52% of near-soft trials. Because they were instructed to reach on every trial, their frequency of reaching is not evidence of their near/far judgment, as it is assumed to be for infants. However, adults' accuracy in contacting the object on near trials suggests that they correctly identified the sounding object's orientation at 45°, and did not err laterally in the hemifield even when the sound was soft and they may have judged it to be in the far location.

C. Adults—Experiment 2

Results from experiment 1 indicate that whereas adults relied on SPL as a major depth cue, infants did not. Both groups of infants were capable of distance discrimination in the dark, because they reached into the target area more often when the object was within reach. One possibility is that the infants, who were not constrained on their parent's lap, gained interaural and spectral auditory cues from head motion. Clifton *et al.* (1991) reported that infants produce large movements of the head and torso in the dark prior to making contact with the object. Although there is no proof that infants' distance discrimination in the present study was aided by head movements, the cues were certainly available for use. Similarly, studies with adult listeners have shown that head movements (Thurlow *et al.*, 1967; Thurlow and Runge, 1967) and motion of the listener's body (Ashmead and LeRoy, 1992) reduce error rates in localization tasks. In the present study cues resulting from head motion would not have been available to adult subjects who were asked to maintain their heads in a fixed position throughout the experiment.

An additional group of 10 adults (5 male, 5 female; mean age $= 23 \pm 4$ yr; range $=$ 19–28 yr) with normal hearing according to self-report were tested on the verbal component. All subjects received the experimental protocol, which included both SPLs at both distances. The procedure and stimuli were identical to those from experiment 1, except that subjects were blindfolded and tested in the light. They were instructed to move their heads in the dark in order to maximize depth cues prior to making a judgment about distance of the sound. They were told to move their heads back and forth, as well as up and down and rotating. If subjects did not move their heads appropriately, they were instructed to do so by the experimenter.

Results from this experiment were compared with those of experimental subjects in the experiment 1. The proportion of trials on which subjects' responses were correct was analyzed with a 3-way ANOVA of group (head movement versus no-head movement) $\times$ distance (near versus far) $\times$SPL (67 dB vs 74 dB). Results were the same as in experiment 1: a significant effect of distance [$F(1,28) = 5.523$, $p < 0.026$], with a higher proportion of correct responses on near than far trials, and a significant interaction of distance by SPL [$F(1,28) = 87.342$, $p < 0.001$]. No main effects of group ($p > 0.43$) or SPL ($p > 0.68$) and no other interactions ($p > 0.7$) were observed. The lack of a group effect indicates that adults' performance was not improved by head movement in the dark. The hypothesis was not supported that the age differences obtained in experiment 1 were due to the infants' head movement in the dark.

III. DISCUSSION

The use of SPL as a cue in auditory distance discrimination was tested in infants and adults by presenting them with sounding objects in the dark. Infants reached for the sounding object more often when it was presented close enough to grasp than when it was presented beyond their reach, replicating a previous report using the same technique (Clifton *et al.*, 1991). Infants correctly discriminated distance regardless of whether SPL changes corresponded to or randomly varied with the sound source's location. This finding does not prove that infants are insensitive to distance variations in SPL, nor that they are unable to use such variations as a cue for judging distance. One would have to eliminate all distance cues but level changes to reach this conclusion. However, our data do suggest that infants can use cues other than SPL, although the question remains as to what these might be. By contrast, adults were misled by the random variations in SPL, and chose location on the basis of whether the sound was loud or soft, with little regard for actual location. This result would be expected on the basis of previous work that indicated the dominance of SPL cues in adults' distance judgments (Ashmead *et al.*, 1990; Coleman, 1963; Mershon and King, 1975). These reports also found that adults could discriminate distance using cues other than level, though performance was usually poorer. In the study most relevant to ours, Ashmead *et al.* (1990) tested adults' distance thresholds with a reference "far" point at 1 m (same as the far sound in the current study) and a variable "near" point that changed in 1-cm steps. With the SPL cue available, subjects' thresholds averaged 5.73 cm, but when this cue was removed thresholds rose to 16.34 cm. These authors removed the cue in the same manner as in the present study, by adjusting SPL at the adult's head to be equivalent across varying distances. Our distance difference (100 cm vs 15 cm) was much greater than in Ashmead *et al.*, and their data would predict it to be easily discriminated even without level cues. However, Ashmead *et al.* practiced their subjects beforehand, gave feedback after each trial, and established threshold with the standard two-down, 1-up algorithm (Levitt, 1971), all of which would work toward better performance than our adult procedure, which was designed to replicate the brief infant session of eight trials with no feedback.

Our procedures did not allow a direct comparison of infants' and adults' accuracy in discriminating distance. Adults could be correct by chance on 50% of all trials in this two-alternative task, whereas infants had only one way to be correct on each trial type (by reaching into the target area on near trials and not reaching at all on far trials), yet many ways to be wrong. They could reach, but reach incorrectly on both trial types; they could fail to reach at all on a near trial; they could reach correctly on a far trial when they should refrain from reaching at all. Viewed this way, the infants exhibited amazingly accurate performances under both types of SPL manipulations. In addition to reaching more often when the sounding object was close than when it was far away, infants were quite accurate when they did reach. The very first reach in the dark on near trials brought the hand into the target area on 80% of the reaches. Considering that the target area occupied only 7% of the reaching space in front of the infant, this is a high degree of accuracy and comparable to that reported previously (Clifton *et al.*, 1991; Perris and Clifton, 1988). When infants reached incorrectly on near trials, hand movements were fairly distributed over the rest of the apparatus (see Fig. 3). When the object was out of reach, infants not only reached less often but also made relatively more incorrect reaches than on near trials. Although reaches on far trials were concentrated in the target area's hemifield, the hand was as likely to be above or below the target area (TER movement type in Fig. 3) or elsewhere in the hemifield (TH) as in the target area itself. Perhaps the greater distance of the sound produced a broadened image, spreading it beyond the target area and encouraging less confined reaches.

In summary, we conclude that SPL once again proved to be an overwhelming cue for adults' distance judgment but was much less potent for infants. Further research is needed to separate out the critical distance information for infants. The most obvious advantage that infants had over adults, i.e., a moving head, was found not to benefit adults in disambiguating SPL confounded with distance. Again, this finding with adults does not rule out the possibility that infants gained distance information from head movement, but it does suggest that other explanations are highly plausible. One possibility concerns a methodological limitation which necessitated that the sounds were presented at shoulder level for infants and midtorso level for adults. Consequently, the distance between the ears and the sound source had vertical angular disparity, which was different for infants and adults at both the near and far positions. It is possible that infants utilized such a vertical disparity cue to solve the distance problem, whereas adults tended to rely more heavily on SPL. Since we know of no data to suggest that vertical angular disparity aids distance discrimination, further studies in this domain are necessary before firm conclusions can be drawn. A second intriguing possibility is that the high-frequency energy of the bell sound in the 16-kHz octave-band range may have produced distinctive distance cues due to spectral changes in interaural difference levels at the two positions. Interaural differences in level are greater for high frequencies than low due to head shadowing, and at very close distances these level differences increase (Blauert, 1983, pp. 73–75). The data cited by Blauert (see especially Figs. 2.24 and 2.27) do not extend to very high frequencies, but the implication in these figures is that interaural level differences would be exaggerated for high frequencies at distances of a few centimeters. These level differences change dramatically with the sound's position in the azimuth, which could be achieved by moving either the head or the sound. Infants' sensitivity to high frequencies is well-documented (Schneider *et al.*, 1980), whereas these very high harmonics may have been less audible to adults. This may have worked to the infants' advantage, although adults with excellent high-frequency hearing would have this distance information available. Future work on distance perception in infants should consider both the possibility of head movement facilitation and very high-frequency sensitivity, as well as the relation between these two.

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