Sound localization with a preceding distractor[a)]

Norbert Kopčo, Virginia Best, and Barbara G. Shinn-Cunningham[b)]
Hearing Research Center, Boston University, Boston, Massachusetts 02215

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Experiments explored how a distractor coming from a known location influences the localization of a subsequent sound, both in a classroom and in an anechoic chamber. Listeners localized a target click preceded by a distractor click coming from a location fixed throughout a run of trials (either frontal or lateral). The stimulus onset asynchrony (SOA) between distractor and target was relatively long (25–400 ms); control trials presented the target alone. The distractor induced bias and variability in target localization responses even at the longest SOA, with the specific pattern of effects differing between the two rooms. Furthermore, the presence of the distractor caused target responses to be displaced away from the distractor location in that run, even on trials with no distractor. This contextual bias built up anew in each run, over the course of minutes. The different effects illustrate that (a) sound localization is a dynamic process that depends on both the context and on the level of reverberation in the environment, and (b) interactions between sequential sound sources occur on time scales from hundreds of milliseconds to as long as minutes. © *2007 Acoustical Society of America.* [DOI: 10.1121/1.2390677]

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I. INTRODUCTION

Everyday settings typically contain multiple, uncorrelated sound sources coming from different locations. In order to respond appropriately to events, listeners in such settings often must estimate the locations of the sound sources. Even in environments with only a single acoustic source, this task is computationally demanding because the brain must compute source location from the acoustic signals received at the two ears. Multiple factors influence localization of single sources, from the way in which sound propagates in the environment to the way in which information is processed by the listener (see also Middlebrooks and Green, 1991). Our understanding of the factors that influence localization in scenes with *multiple* sound sources is very limited.

Previous studies of how a simultaneous masker influences target localization show that perceived target location can either be "attracted towards" or "repulsed away from" the masker location, depending on the stimulus characteristics and configuration (e.g., Butler and Naunton, 1962; Good and Gilkey, 1996; Heller and Trahiotis, 1996; Braasch and Hartung, 2002; Best *et al.*, 2005). However, two stimuli do not have to overlap in time in order to interact perceptually. For example, a stimulus that immediately precedes a target can act as a masker that interferes with the detection of the target (a phenomenon known as "forward masking," see, e.g., Kollmeier and Gilkey, 1990) or as an adaptor that introduces biases in the perceived location of the target (Thurlow and Jack, 1973; Kashino and Nishida, 1998; Duda *et al.*, 1999; Carlile *et al.*, 2001; Phillips and Hall, 2005).

In the "precedence effect," a sound arriving shortly after a preceding sound has little influence on perceived location, to the point that listeners are even poor at detecting changes in the spatial cues in the second sound (for a review, see Litovsky *et al.*, 1999). This phenomenon is often invoked to explain why listeners are able to localize sounds relatively accurately in reverberant space (Hartmann and Rakerd, 1999). The neural mechanism underlying the precedence effect is thought to suppress spatial information contained in later-arriving sounds ("lag discrimination suppression") as well as reduce the likelihood of hearing later sounds as new, discrete events ("echo suppression"). Moreover, the precedence effect builds up over time, such that the likelihood of perceiving reflections as unique events decreases with repetition (Clifton and Freyman, 1997). These effects have been characterized experimentally by presenting pairs of "lead" and "lag" stimuli in a simulated or real anechoic environment. In such conditions, echo suppression is observed for lead-lag delays of up to 10 or 20 ms for impulsive sounds (although the suppression can last up to 50–100 ms for ongoing sounds such as speech and music; Zurek, 1987). Of course, localization suppression of a second sound in a reverberant space may last longer than the suppression seen in typical precedence effect studies, as the reverberant energy from a preceding sound may help suppress localization cues in the second sound as well as reduce the saliency of the second sound onset (e.g., see Roberts *et al.*, 2004).

There are hints that spatial perception of a sound source can be affected by another sound source even when the two sources are separated considerably in time. For example, the minimum audible angle (MAA) paradigm (Mills, 1958) involves the sequential presentation of two stimuli in order to measure the smallest detectable change in source angle from one stimulus to the next (the MAA). Several studies have shown that the MAA depends on the stimulus onset asynchrony (SOA) between the first and the second stimulus for SOAs of up to 150 ms (see, e.g., Perrott and Pacheco, 1989;

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[b)] Author to whom correspondence should be addressed. Electronic mail: shinn@bu.edu

Strybel and Fujimoto, 2000). Furthermore, two preliminary studies of localization with a preceding auditory cue (Kopčo *et al.*, 2001; Kopčo and Shinn-Cunningham, 2002) showed that the cue can have a complex effect on localization of a subsequent target for temporal separations up to hundreds of milliseconds.

Finally, several neurophysiological studies show that a preceding stimulus modulates the neural response to a target stimulus in a spatially dependent manner (Yin, 1994; Litovsky and Yin, 1998; Fitzpatrick *et al.*, 1999; Reale and Brugge, 2000). This modulation is observed for SOAs of tens of milliseconds in the inferior colliculus and hundreds of milliseconds in the auditory cortex, comparable to the time scales observed in many psychophysical studies.

The goal of the current study was to begin to characterize long-lasting spatial interactions between successive sound sources and the factors affecting these interactions. The experiments measured how the perceived lateral angle of a single-click target stimulus is influenced by an identical stimulus presented before the target from a different azimuthal location. A large range of time scales was investigated, with SOAs ranging from 25 to 400 ms. Several factors are likely to influence performance on this task, acting across different time scales (see Sec. IV A for more discussion). For example, relatively peripheral interactions are likely to contribute with a strength that decreases with increasing SOA, whereas more central factors may affect performance in ways that depend more weakly on SOA (e.g., affecting the strategy a listener employs in responding under different circumstances).

Two experiments were performed: one in a small classroom (Experiment 1) and the other in an anechoic chamber (Experiment 2). We attribute any differences in performance across the experiments to the presence of reverberant energy, either because of interference between the reverberant energy from the distractor and the direct sound energy from the target (acoustic interactions) and/or because of the effect of reverberant energy from the distractor on processing of the location information from the target (neural interactions).

II. GENERAL METHODS

A. Subjects

Seven subjects (three female and four male) participated in Experiment 1. All subjects had normal hearing as confirmed by audiometric screening, with ages ranging from 23 to 32 years. Four listeners (one female and three male) had prior experience in psychoacoustic experiments (including authors NK and VB). The four experienced listeners were the only participants in Experiment 2.

B. Stimuli and setup

Distractor and target stimuli each consisted of a single click (rectangular envelope of 2 ms duration) presented at 67 dB sound pressure level (SPL) (A-weighted maximum rms value in a 2 ms running window at the location of the listener's head). The measured spectrum in third-octave bands was flat from 2 to 4 kHz, with a 6 dB per octave roll-off outside the band. The stimuli were generated by a PC-controlled Tucker Davis Technology System 3, amplified by a Crown D-75A amplifier, and played by one of nine matched Bose Acoustimass cube loudspeakers selected by a serial-port-controlled eight-relay output module (KITSRUS K108). Analysis of recordings of the stimuli showed differences between loudspeakers of no more than 5 dB in any third-octave band over 700–16,000 Hz. The stimulus onset asynchrony (SOA) between the distractor and the target click was set to 25, 50, 100, 200, or 400 ms.

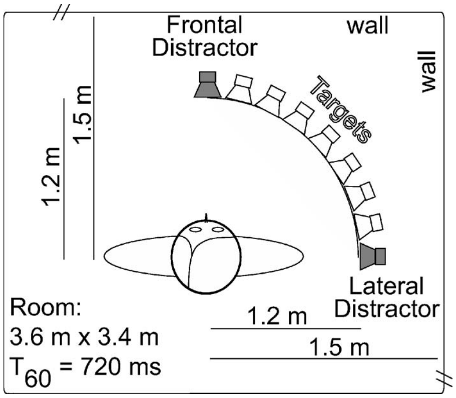

FIG. 1. Diagram of the orientation and location of the listener and the loudspeakers in the classroom used in Experiment 1. The same setup was used in the anechoic chamber in Experiment 2 although the (acoustically transparent) chamber walls were at different distances. In the figure the listener is facing the left-most loudspeaker and the targets are on his/her right. In half of runs, the listener was oriented to face the right-most loudspeaker and the targets were on his/her left.

A Polhemus FastTrak electromagnetic tracker was used to measure the location of the listener's head, the approximate location of the loudspeakers, and the listener's responses. The listeners indicated the perceived direction of the target source by pointing a stick with the Polhemus electromagnetic sensor attached at its end and pressing an attached button. Note that the listeners were allowed to point in any direction, including outside the range of target directions. Moreover, they were specifically instructed to point in the perceived direction of the sound. However, given the subjects' familiarity with the experimental setup, they may have limited their responses to fall within the actual speaker range even if they perceived the target as outside of this range.

The nine loudspeakers were equally spaced along a quarter circle of diameter 1.2 m with the listener at the center (Fig. 1). The loudspeakers were fixed on stands 1.5 m above the floor, approximately at the level of the listener's ears. The listener was seated on a chair that could be rotated so that they faced the left-most or the right-most loudspeaker, with the loudspeaker array either in their right or left frontal quadrant (respectively). The left-most and right-most loudspeakers were used only to present the distractor stimuli. The remaining seven loudspeakers were used to present target stimuli. An additional loudspeaker directly behind the listener played instructions to the listener during the experiment.

C. Listening environments

Experiment 1 was conducted in an empty, quiet rectangular classroom measuring 3.4 m × 3.6 m × 2.9 m (h), with a small entrance space measuring 1.5 m × 1.6 m × 2.9 m. The room was carpeted, with hard walls and acoustic tiles covering the ceiling. The reverberation times in octave bands centered at 500, 1000, 2000, and 4000 Hz were 613, 508, 512, and 478 ms, respectively. The background acoustic noise was at approximately 39 dB SPL (A-weighted). As illustrated in Fig. 1, the loudspeaker array was set up in a corner of the room with the left-most and the right-most loudspeakers 30 cm from and facing away from the two nearest walls. The listener was seated 1.5 m from these walls.

Experiment 2 was conducted in an anechoic chamber at the Dept. of Psychology of the University of Massachusetts, Amherst. The chamber measures 4.9 m × 4.1 m × 3.12 m and its walls, floor, and ceiling are lined with 0.72 m foam wedges. The subjects were seated near the center of the chamber as illustrated in Fig. 1; the only difference in setup from Experiment 1 was that there were no reflective walls.

D. Experimental procedure

Each experiment consisted of four 30 min blocks, separated by breaks. Within each block, the listener performed four runs, one for each combination of listener orientation (facing the left- most or the right-most loudspeaker) and distractor location (from the left-most or the right-most loudspeaker). The order of the runs within each block was random, and differed from subject to subject. Each run contained 168 trials [seven (target loudspeaker locations) × six (five SOAs + no distractor) × four (repeats)]. Within each run, one repeat of each of the six conditions (five SOAs and the no-distractor control) was presented in random order before any condition was repeated, so that each run logically could be broken down into four subruns.

At the beginning of each run the subject was instructed to rotate the chair to face the predetermined loudspeaker, sit on the chair, and put his/her head on the headrest. After calibration measurements (see below), the listener was instructed to close his/her eyes and remain still for the remainder of the run. The listener was told which loudspeaker would present the distractor in the run, and a sample stimulus (a pair of clicks, one from the distractor loudspeaker and one from one of the randomly selected target loudspeakers) was presented before the experimental trials began.

A single trial consisted of a presentation of one stimulus, followed by the listener's response, after which there was a constant delay (approximately 0.5 s) before the stimulus for the next trial was presented. With this inter-trial delay, the subject had no difficulty in reorienting from indicating the previous location to preparing for the next stimulus. There was no limit on how fast the subject had to respond, so the pace of the experiment was controlled by the subject. On average, a trial took 2–3 s and a run took 5–6 min.

Each stimulus contained one target click presented from a randomly chosen target loudspeaker. In a majority of the trials (five out of six, i.e., 83%), a distractor click was also presented before the target; on the rest of the trials there was no distractor, but the target click was preceded by 400 ms of silence in addition to the standard inter-trial pause (this additional delay came about because the no-distractor stimulus was derived from the 400 ms SOA distractor stimulus by zeroing the distractor channel). The listener did not know a priori whether or not a given trial would contain a distractor, but could always tell whether one or two sources had been presented. In addition, although listeners were not instructed about the timing of the stimuli explicitly, they rapidly learned that no-distractor trials began with a 400 ms silence, which cued them to expect a target-only trial. After each stimulus, the listener pointed in the perceived direction of the target and pressed a button that caused the response to be recorded and the next trial to be initiated.

In Experiment 1 the subjects performed 1–2 blocks per day. In Experiment 2 the subjects performed the whole experiment in one day. In both experiments, the blocks were interleaved with blocks of another similar study; however, in each case there was at least 1 h of rest between consecutive blocks.

At the beginning and end of every run, subjects calibrated the electromagnetic tracker's coordinate system. With his/her eyes open, the subject was asked to point the electromagnetic pointer at the center of the two distractor loudspeakers and at the middle target loudspeaker. He/she was then asked to establish the location of the head by pointing at (in this order) his/her left ear, right ear, and nose. Because subjects actively and frequently performed this calibration, they were highly familiar with the layout of the loudspeakers.

At the beginning of Experiment 1, the experimental procedure was described to the listeners. In particular, the listeners were instructed to try to ignore the distractor, that the distractor and no-distractor trials would be interleaved within a run, and that they should point in the *perceived* direction of the target, regardless of what they knew about the experimental setup and the possible speaker locations. In addition, the purpose of the calibration measurements was explained and it was stressed that the listeners should not move their heads or open their eyes during a run (i.e., between the initial and final calibration measurement). After receiving these instructions, the listeners performed a brief practice session consisting of at least two runs.

E. Data analysis

All subject responses, recorded by the tracker in the form of Cartesian coordinates, were first projected into the plane defined by the recorded location of the three loudspeakers and the center of the listener's head. These recorded locations were determined by averaging the calibration measurements taken at the beginning and the end of each run. The lateral angle between the response direction and straight ahead (with respect to the center of the head) was calculated and stored as the response angle. Analysis showed negligible left-right differences, so the data measured with the subjects facing the right-most loudspeaker were mirror flipped and combined with the data measured when the subjects faced the left-most loudspeaker. This reduced the four spatial configurations to two: one with a frontal distractor and one with a lateral distractor. For each subject, 32 responses were col-

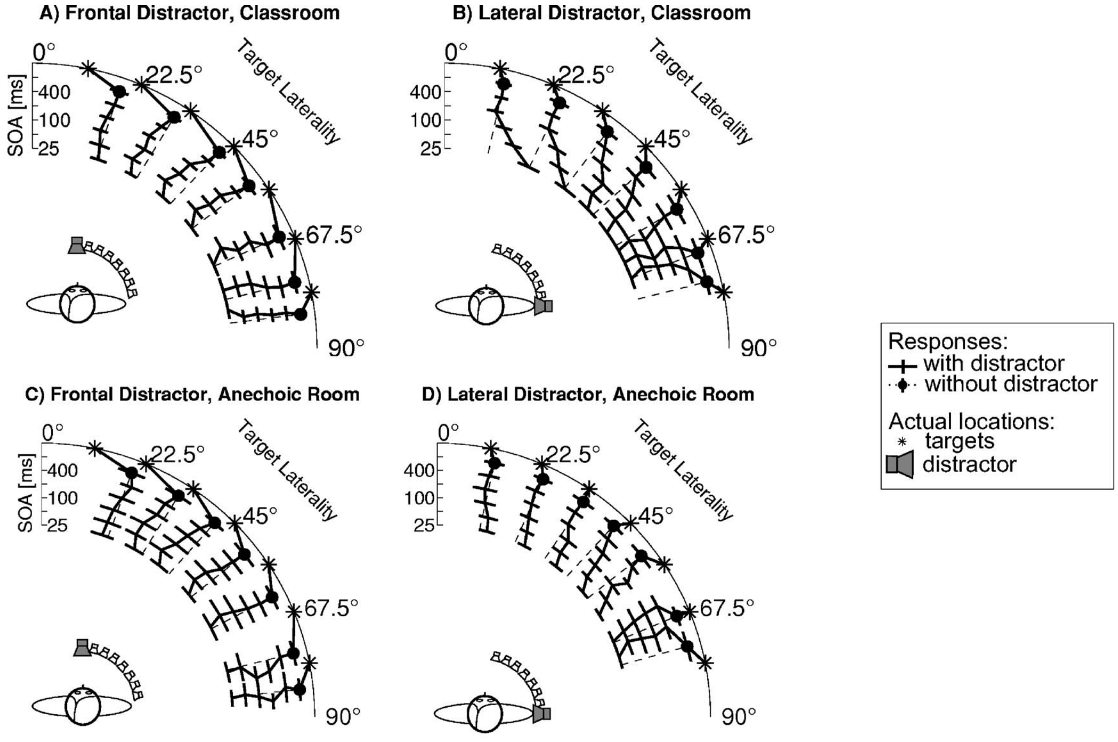

FIG. 2. Mean localization responses in the classroom (A, B) and the anechoic room (C, D). Each panel shows the across-subject mean and standard error in perceived target lateral angle as a function of actual target lateral angle for different SOAs, as well as in the no-distractor condition. A, C) Frontal distractor. B, D) Lateral distractor.

lected in total for each combination of configuration (frontal vs lateral distractor), SOA (five SOAs + no distractor), and target lateral angle (seven lateral angles).

III. RESULTS

A. Experiment 1: Classroom

The top two panels of Fig. 2 show the across-subject mean and standard error in the perceived target location as a function of the actual source lateral angle for frontal (panel A) and lateral (panel B) distractors (the bottom two panels show results for Experiment 2, discussed in Sec. III B). The asterisks in both panels show the actual lateral angles of the target loudspeakers. The radial solid lines connected to each asterisk (target location) show the average response angles for the different stimulus conditions. Each crossing of a radial line with a line segment shows a mean response angle, with the length of the segment showing the standard error in the mean response for a given target lateral angle and SOA. The outermost data points (filled circles) represent the control-trial responses with no distractor, followed by the responses obtained with an SOA of 400 ms. Further decreases in the radial distance correspond to gradually smaller SOAs, with the 25 ms SOA shown by the innermost ring of data. A dashed radial line starting at the no-distractor response location (filled circles) is shown to allow the effect of the distractor on the perceived target lateral angle to be easily assessed.

1. Contextual bias

One large effect evident in Fig. 2(A) is that for blocks involving the frontal distractor, localization responses are biased towards the side, shown by a clockwise displacement of all judgments (even on trials where the distractor is not present; compare asterisk locations to all mean response angles). For blocks involving the lateral distractor, the most lateral targets are biased towards the midline, while more frontal targets show a slight opposite bias, towards the side (Fig. 2(B); compare asterisks and filled circles). Overall, a consistent response bias is evident: responses are more lateral for the frontal distractor than for the lateral distractor. These biases are caused by the ensemble of trials presented in a given experimental run, not by the immediately preceding distractor, because they occur for all trials, including the no-distractor control trials. Note that there were no control runs made up entirely of control trials, so we cannot directly determine exactly what response bias is caused by the distractor presented in a particular run. However, we can directly compare the bias observed for trials in frontal- and lateral-distractor runs to assess the change in bias caused by changing the distractor location from frontal to lateral in different runs.

To quantify this context effect, we computed the difference in responses for the same target location and SOA for both frontal- and lateral-distractor runs. For each subject and target direction, the mean response in the lateral-distractor runs was subtracted from the mean response for the frontal-distractor runs. These results are shown in Fig. 3, averaged

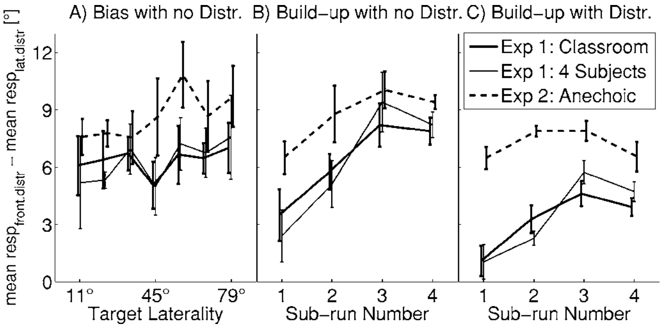

FIG. 3. Contextual effects observed in the no-distractor trials (A, B) and in the distractor trials (C). Performance for all seven subjects from Experiment 1 is shown by thick solid lines, for a subset of four subjects by thin solid lines, and for Experiment 2 by dashed lines. The statistic plotted in each panel is the across-subject mean and within-subject standard error[1] in the: A) difference between the perceived target location in the context of frontal vs lateral distractor as a function of target lateral angle; B) across-lateral-angle average difference in responses as a function of subrun within experimental run; C) across-lateral angle and across-SOA average difference in responses in trials with distractor as a function of the subrun number within experimental run.

across subjects. Panel A shows the overall magnitude of the change in response bias for the no-distractor control trials as a function of target laterality. Panel B shows the magnitude of the effect for the no-distractor trials as a function of time within a run, collapsed across target location. Panel C shows the magnitude of the effect for the distractor trials, collapsed across SOA and target location, as a function of time within a run. The solid thick lines in Fig. 3 plot the across-subject mean effect for the seven subjects who completed Experiment 1. The solid thin lines show the results in Experiment 1 averaged over the subset of four subjects who performed both Experiment 1 and Experiment 2. The dashed line shows the same results (for the same four common subjects) for Experiment 2 (these results are discussed below, in Sec. III B). Error bars in each panel show the within-subject standard error of the across-subject mean.[1]

In general, Fig. 3 shows that the four subjects who performed both Experiment 1 and Experiment 2 show the same pattern of results in Experiment 1 as the larger subject population (compare thick and thin lines in each panel).

Figure 3(A) quantifies the influence of the distractor on the no-distractor trials as the difference in the mean response on no-distractor trials for frontal- and lateral-distractor runs. For all target angles this difference is positive (thick and thin solid lines in Fig. 3(A)). In other words, distractors cause response bias within a run such that the no-distractor control trial responses are relatively closer to the median plane when the distractor is to the side and relatively farther from the median plane when the distractor is in front. Computed as the difference between the response bias in the lateral- and frontal-distractor runs, the contextual bias is roughly independent of target laterality (i.e., the solid lines in Fig. 3(A) are relatively flat).

Because the experimental runs with the frontal and lateral distractors were interleaved, any contextual shift caused by the distractors had to develop anew in each experimental run. Each run consisted of 168 trials: four repeats of each combination of target lateral angle and SOA condition. Trials within a run were ordered in subruns, such that all combinations of target angle and SOA were presented once before any were repeated. Thus, in each run, exactly four full sets of no-distractor responses (one for each of the seven target locations) were measured, one in each subrun. Because there was no large effect of target lateral angle on the contextual bias in the no-distractor responses (see Fig. 3(A)), data were combined across the target angle for each subject to estimate the contextual effect as a function of subrun.

Figure 3(B) shows the across-subject mean in the contextual difference as a function of subrun. In general, the contextual effect increased with subrun. Averaged across all seven subjects, the contextual effect grew from roughly 4 to 8° across the four subruns (solid thick line; one-way repeated measures analysis of variance (ANOVA): $F_{3,18}=7.64, p<0.005$). The buildup was also significant when considering only the four subjects who also completed Experiment 2 (solid thin line; one-way repeated-measures ANOVA: $F_{3,9}=17.52, p<0.0005$). Given that one experimental run took approximately 5 min, this result shows that the context effect built up over the course of minutes, orders of magnitude longer than the millisecond time scale of primary interest in this study.

Figure 3(C) plots the contextual bias within each subrun for the distractor trials (collapsed across SOA and target angle) to see if this buildup was general. Although the average contextual bias for the distractor trials is smaller than for the no-distractor trials, the contextual bias builds up over subruns in a way that is similar to that seen in the no-distractor trials (compare the solid thick and thin lines in Figs. 3(B) and 3(C); the difference in the change in contextual bias over time is roughly 2° or less across all subruns). The increase in contextual bias with subrun for the distractor trials is significant both for the full set of seven subjects (solid thick line; one-way repeated-measures ANOVA: $F_{3,18}=4.05, p<0.05$) and for the subset of four subjects who also performed Experiment 2 (solid thin line; one-way repeated-measures ANOVA: $F_{3,9}=9.95, p<0.005$).

Taken together, these results show that there is an unexpected effect of the distractor on localization of the target that builds up over time for both control and distractor trials. This suggests that, in the absence of any measurements of localization in blocks without any distractors, the most appropriate controls for judging the effect of an immediate distractor are the responses to the control trials within a block.

2. Effect of distractor on mean responses

Figures 2(A) and 2(B) show that the distractor causes different biases at different SOAs. However, inter-subject differences are large, as indicated by the standard errors in the means. Some of this inter-subject variability may be due to individual differences in the average response biases present across all trials in a run (including the no-distractor control trials). Therefore, differences between the responses for targets preceded by distractors and responses in the no-distractor control trials were computed for each subject individually (for each run). Having established that both control and distractor trials are similarly affected by the built-up

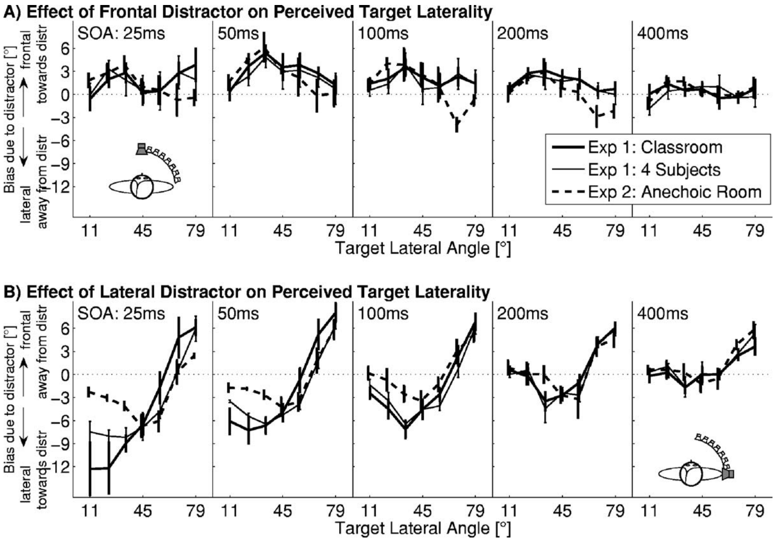

FIG. 4. Effect of the distractor on the perceived target lateral angle in the classroom and the anechoic room. Plotted is the across-subject mean and standard error in the difference between the perceived lateral angle with the distractor vs without the distractor. Each panel shows results for a different SOA. A) Frontal distractor. B) Lateral distractor.

contextual bias, these differences show the effects of the immediately preceding distractor on performance.

Figure 4 shows the within-subject change in localization response due to the presence of the distractor, averaged across subjects (error bars show the standard error in this within-subject difference). Positive values in Fig. 4 correspond to bias towards midline; negative values represent a bias to the side. The solid thick lines in Fig. 4 show results for the full set of seven subjects in Experiment 1. The solid thin lines show results for the subset of subjects who completed both experiments. Finally, the dashed line shows results for the same four subjects in Experiment 2 (discussed in Sec. III B).

As seen by the smaller size of the standard errors in Fig. 4 compared to Fig. 2, the effects of the distractor are much more consistent across subjects when computed relative to each subject's individual no-distractor response. In general, results for the full set of seven subjects who performed Experiment 1 are very similar to results for the subset of four subjects common to both experiments (compare solid thick and thin lines in Fig. 4), although the magnitude of some of the biases is smaller for the subset of four subjects (e.g., the thin solid lines tend to fall above the thick solid lines in the left edges of the left-most panel of Fig. 4(B)).

Several effects of the distractor on target localization can be observed in the reverberant classroom:

- For frontal targets, the lateral distractor causes a bias towards the side, an effect that decreases with increasing SOA. For instance, for an SOA of 25 ms (left-most panel of Fig. 4(B)), the left edge of the solid line shows a bias that is 12° on average; however, this effect is not present for an SOA of 400 ms (the right-most panel in Fig. 4(B)).
- Both the frontal and the lateral distractors cause targets located at intermediate source angles (near 45°) to be localized closer to the distractor. The average size of this effect is as large as 6° and decreases with increasing SOA. For instance, in the solid lines in Fig. 4(A), response bias is positive for intermediate target lateral angles at SOAs of 25 and 50 ms, but is negligible for an SOA of 400 ms. Similarly, in Fig. 4(B) there is a negative dip in the response bias for intermediate lateral angles that decreases with increasing SOA.
- The lateral distractor causes a bias in the localization of nearby targets towards the midline, an effect that is independent of the SOA. In Fig. 4(B), the right edge of each solid line is positive, falling at around 5°.

3. Standard deviation in responses

For each subject, the standard deviation in the responses was computed for each combination of target lateral angle, SOA (including the no-distractor condition), and distractor location. These standard deviations were subjected to a three-way repeated-measures ANOVA with factors of SOA, distractor angle, and target angle. For the full set of seven subjects, this analysis found a significant interaction between SOA and target location ($F_{30,180}=1.63, p<0.05$) as well as a significant main effect of SOA ($F_{5,20}=26.16, p<0.0001$). For the subset of four subjects who completed both experiments, the same ANOVA found a significant three-way interaction between SOA, distractor location, and target location ($F_{30,90}=1.59, p<0.05$) and a significant main effect of SOA ($F_{5,15}=18.40, p<0.0001$). All other interactions and main effects were not significant. This analysis suggests that response variability changes with SOA in a manner that depends upon distractor location and target location.

Figure 5 shows the across-subject means in the standard deviations as a function of target laterality for two SOAs (the shortest SOA of 25 ms and an intermediate SOA of 100 ms, shown by triangles and squares, respectively) and for the no distractor condition (shown by circles). Data for the other SOAs are left out to improve the figure legibility, but followed the trends illustrated by the data included in the figure. The error bars in Fig. 5 represent the within-subject standard errors of the means.[1] Panels A and B show the data from Experiment 1 for the frontal and lateral distractors, respectively. Data for all seven subjects are shown in the upper portion of panels A and B; data for the subset of four subjects

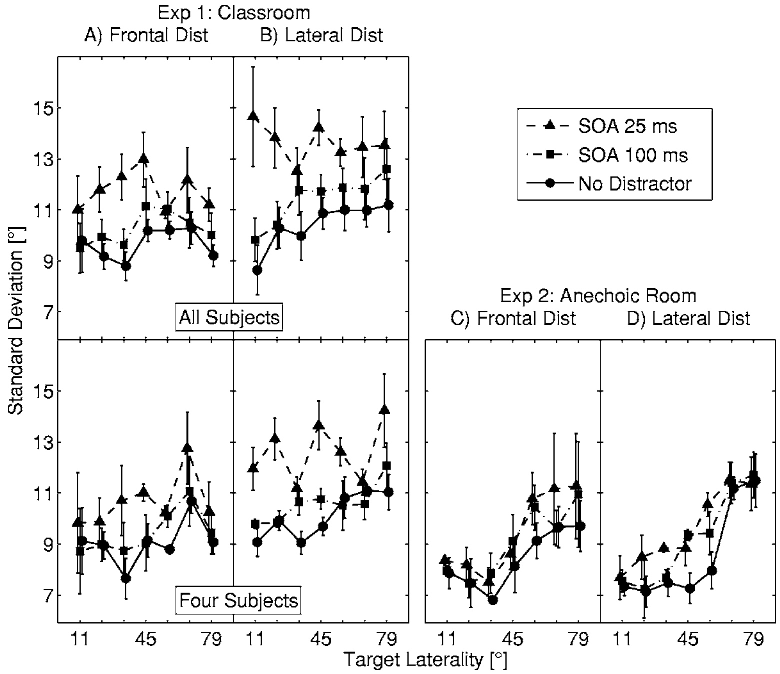

FIG. 5. Standard deviations in listeners' responses in the classroom (Exp 1, panels A and B) and the anechoic room (Exp 2; panels C and D) as a function of the target laterality for two example SOAs and the no-distractor condition (results for other SOAs follow the same trends, and are left off for visual clarity). The across-subject means in the standard deviations are shown (error bars show within-subject standard error of the mean). A, C) Frontal distractor. B, D) Lateral distractor. Upper portion of panels A and B: all seven subjects. Lower portion: four subjects who participated in both experiments.

who completed both experiments are in the lower portion. Panels C and D show the data from Experiment 2, discussed in Sec. III B.

Overall, the average variability in subject responses was larger for the full set of seven subjects than the subset of four subjects who completed both experiments (data in upper portion of panels A and B are above the corresponding data in the lower portion). However, all other patterns are similar for the two subject groups. In Experiment 1 (panels A and B), variability is larger with a lateral distractor than with a frontal distractor (data in Fig. 5(A) fall below the corresponding data in Fig. 5(B)). For both distractor positions, response variability is greatest at the shortest SOA and smallest when there is no distractor present (within Figs. 5(A) and 5(B), triangles fall above squares, which are above circles). The effect of SOA on response variability tends to be larger for the lateral distractor than for the frontal distractor (compare Figs. 5(A) and 5(B)). This difference did not reach statistical significance with the full set of subjects (i.e., neither the main effect of distractor location nor any of the interactions including distractor location reached significance), but the significant three-way interaction for the subset of four subjects supports this conclusion. For a frontal distractor, variability is essentially independent of target laterality (in Fig. 5(A), results are essentially flat). For a lateral distractor, variability is large and does not show any clear trend as a function of target laterality at the shortest SOA (triangles in Fig. 5(B)); however, at longer SOAs and in the absence of a distractor, variability tends to increase with increasing source laterality.

B. Experiment 2: Anechoic environment

The bottom two panels of Fig. 2 show the results of Experiment 2 in a format identical to the top two panels. As in Experiment 1, when the distractor is in front there is a consistent clockwise displacement of all the judgments relative to the true loudspeaker angle, when the distractor is in front (Fig. 2(C)). The lateral distractor causes a weaker, opposite bias relative to the true target location (Fig. 2(D)), but, as in Experiment 1, this effect is evident only for the target angles near the distractor.

1. Contextual bias

To quantify the context effect, we computed the difference in mean responses on no-distractor control trials between frontal- and lateral-distractor runs as in Experiment 1. Mean differences are shown in Fig. 3(A) (dashed lines; error bars show the within-subject standard error of the across-subject mean[1]). As in the classroom, this difference is positive at all target lateralities and roughly independent of target laterality. The context effect tended to be slightly greater in anechoic space than in the classroom (in Fig. 3(A), the dashed line is above the solid and the thin lines), although this difference did not reach statistical significance.

The dashed line in Fig. 3(B) shows the across-subject mean in the contextual difference as a function of the subrun in Experiment 2. As in Experiment 1, the contextual bias built up over the four subruns, growing from roughly 6 to 9° (one-way ANOVA with subrun as the factor; $F_{3,9}=5.15$, $p<0.05$).

Distractor trials were analyzed to see if the contextual bias is general (dashed lines in Fig. 3(C)). As a function of subrun, the contextual bias for the distractor trials in the anechoic room was relatively flat (consistent with this, there was no statistically significant effect of subrun on the contextual bias; $F_{3,9}=1.59, p=0.26$). Despite this, the average contextual bias observed across all SOAs and target angles is nearly as large for distractor trials as it is for the no-distractor trials in Experiment 2 (a two-way repeated-measures ANOVA with factors of subrun and distractor presence/absence found no significant interaction; $F_{3,9}=3.05$, $p=0.08$). This suggests that, as in Experiment 1, localization of the no-distractor targets within the runs provides a control for assessing the effect of the immediately preceding distractor on target localization.

2. *Effect of distractor on mean responses*

As in Experiment 1, data were individually normalized by the no-distractor responses and re-plotted (dashed lines in Fig. 4).

Comparing anechoic and classroom results shows:

- The large lateral bias of frontal targets caused by the lateral distractor in the classroom was much smaller in the anechoic room (compare the left-most edges of the dashed lines to the solid thick and thin lines in Fig. 4(B)).
- Consistent with the classroom data, both the frontal (Fig. 4(A)) and the lateral (Fig. 4(B)) distractors biased localization of targets from intermediate lateral angles towards the location of the distractor. This effect is similar in magnitude in anechoic space and in the classroom and decreases with increasing SOA. For instance, the dashed-line peaks in the plots in Fig. 4(A) and the dashed-line troughs in Fig. 4(B) are comparable to the solid thick- and thin-line results for targets near 45°.
- As in the classroom, the lateral distractor induced a bias of nearby targets of about 5° towards the midline, independent of SOA. Specifically, both dashed and solid lines in all the panels of Fig. 4(B) are positive at their right edges (i.e., for the target at 79°).

3. *Standard deviation in responses*

For Experiment 2, standard deviations were computed in the same way as in Experiment 1. Panels C and D in Fig. 5 show the across-subject means in the standard deviations as a function of the target laterality in a format similar to panels A and B. Overall, response variability in anechoic space is smaller than in the classroom (results in panel C fall below those in panel A, and those in panel D fall below those in panel B). In anechoic space, unlike in the classroom, response variability is essentially the same for frontal and lateral distractors (compare results in Figs. 5(C) and 5(D)). Similar to what was seen in the classroom, response variability tends to decrease with increasing SOA (triangles tend to be highest and circles tend to be lowest within each panel), although the effect of SOA is smaller than in the classroom. In Experiment 2, there is a monotonic increase in response variability with increasing target laterality, an effect that is independent of distractor location or SOA (all lines increase from left to right in Figs. 5(C) and 5(D)). Supporting these conclusions, a three-way repeated-measures ANOVA with factors of SOA, target laterality, and distractor location found statistically significant main effects of SOA ($F_{5,15}=4.13$, $p<0.05$) and target laterality ($F_{6,18}=7.46, p<0.001$), but no other significant effects or interactions.

IV. DISCUSSION

A. Stages of auditory spatial processing

In trying to understand the effects of a preceding distractor on localization, it is useful to first outline various stages of auditory processing at which the presence of the distractor could affect the spatial representation of the target.

For sounds that overlap in time, adding before they enter the ear, simple acoustic interactions between distractor and target stimuli may impact the ability to compute target location. Similarly, even if they do not overlap acoustically, when two sounds occur sufficiently close in time (e.g., within 1 or 2 ms of one another), the responses they elicit in the cochlea will overlap and interfere with one another, directly affecting what target spatial information can be extracted (Tollin, 1998; Hartung and Trahiotis, 2001).

Over slightly longer time scales, there may be temporal interactions (e.g., interactions between excitation and inhibition) within the neural structures that extract spatial parameters from the signals at the two ears, such as the brainstem structures that are known to be sensitive to interaural time and level differences. Such interactions (e.g., at the level of the inferior colliculus) are hypothesized to underlie the precedence effect; for instance, a strong onset may cause a subsequent suppression of spatial cues (Yin, 1994; Litovsky and Yin, 1998; Fitzpatrick *et al.*, 1999; Reale and Brugge, 2000; Litovsky and Delgutte, 2002; Dizon and Colburn, 2006). Such mechanisms undoubtedly influence localization in situations involving sequences of stimuli such as those in the present study, especially in the classroom, where reverberant energy persists through the nominal time delay between the distractor and the target stimulus.

Although there is some debate about the nature of the neural representation of exocentric space formed by integrating the different spatial cues (e.g., Carlile *et al.*, 2001; Stecker *et al.*, 2005) it has often been assumed that dynamic interactions within such a representation can explain spatial interactions between stimuli (Thurlow and Jack, 1973; Kashino and Nishida, 1998; Duda *et al.*, 1999; Carlile *et al.*, 2001; Phillips and Hall, 2005). In particular, adaptation after effects are assumed to arise because a repeated stimulus causes long-lasting changes in neural responses that cause a perceptual warping of auditory space (Kashino and Nishida, 1998; Carlile *et al.*, 2001).

Finally, a preceding distractor may influence sound localization at a cognitive level. For example, a distractor may alter the distribution of spatial attention, causing changes in spatial perception, and/or influence the strategy adopted by a listener when judging the location of the target, causing changes in response patterns.

Although the various effects observed in the current experiment cannot be attributed to any particular processing stage with certainty, below we consider the processing levels most likely to be involved in the various phenomena we observed.

B. Standard deviation effects

Overall, response variability was larger in the classroom than in anechoic space, especially for lateral distractors and short SOAs (Fig. 5). It is possible that this effect was simply related to the presence of direct and reverberant energy from the distractor and/or the target. For example, this energy may have added to the acoustic variability in the spatial cues for target location.

Binaural recordings from a KEMAR manikin in the classroom were taken using the stimuli presented to the listeners (see Appendix for details). These recordings confirmed that at short SOAs, reverberant energy from the distractor was present at the onset of the target. Acoustic analysis was performed to examine whether the effect this overlap has on the target spatial cues is consistent with the observed behavior. The analysis showed that the height of the running interaural cross-correlation peak decreases with decreasing SOA (see also Shinn-Cunningham *et al.*, 2005). Such a reduction in interaural correlation is associated with an increase in the width or blurring of the perceived location of a source (Blauert, 1997; de Vries *et al.*, 2001). Similarly, the reverberant energy of the distractor also tended to reduce the magnitude of interaural level differences (ILDs) at the onset of the target, causing the ILDs to be somewhat inconsistent with the interaural time differences (ITD) cues.

Both of these effects (a reduction in interaural correlation strength and alteration of the mean ILDs in the stimuli) may have caused the target location to be more diffuse and more difficult to localize. Thus, acoustic interactions between reflected energy from the distractor and direct energy of the target may at least partially account for the increase in response variability for sources in the classroom compared to in anechoic space. In addition, there was some, albeit weak, background noise present in the classroom that was not present in the anechoic chamber. Given that the response variability to the control trials is also greater in the classroom than in the anechoic setting, this noise may have further reduced the reliability of the spatial cues in the room and increased the response variability.

A precedence-effect-like suppression of spatial information in sounds following an abrupt onset or preceding sound may also contribute to the larger response variability in the classroom compared to in anechoic space. Although most precedence studies talk about mechanisms that operate only up to about 10 ms, suppression lasts longer for ongoing stimuli such as speech or music. Indeed, reflections from the distractor may directly suppress later-arriving sound location cues (e.g., in the onset of the target sound), or may effectively extend the suppression initiated by the distractor onset (see also Roberts *et al.*, 2004). All of these observations suggest that at least some portion of the greater response variability observed in the classroom compared to in anechoic space may be caused by a neural mechanism invoked by ongoing acoustic energy occurring just before the onset of the target (in this case, the reflected energy of the distractor).

It is worth noting, however, that neither the acoustic analysis nor consideration of precedence-like suppression can explain certain details of the response variability data. For example, neither explanation can account for why, in the classroom, response variability is larger for lateral distractors than for frontal distractors.

C. Biases

The most prominent effect of the distractor in these experiments was that in the classroom, the lateral distractor biased the perceived location of frontal targets towards the side at short SOAs. Given that this effect is much weaker in anechoic space, one parsimonious explanation for this bias is that the lateral distractor and its reflections interacted acoustically with the target. However, analysis of the spatial cues in the total signal reaching the listener at the target onset (see Appendix) did not reveal any biases in the interaural parameters that would predict the observed shift in perceived lateral position towards more lateral positions. In particular, there is no consistent bias in the ITD value corresponding to the peak in the interaural cross-correlation function at the target onset. While ILD cues do show a systematic bias, this bias is in the wrong direction to explain the observed behavioral bias. The magnitude of the ILDs in the acoustic signals is reduced by reverberant energy, an effect that, if anything, should result in perceived target positions being biased towards, not away from, the median plane.

It may be that the localization bias of frontal targets by a lateral distractor is related to the variability in the subject responses, discussed above. Specifically, the listeners might be biased to respond towards the middle of the response range whenever they are uncertain about the target location. Indeed, response variability is greatest for lateral distractors in the classroom, particularly when the SOA is short (e.g., see triangles plotted in the left edge of Fig. 5(B), compared to all other results in Fig. 5), the very conditions that produce the greatest response bias (Fig. 4(B), left edges of the first and second panels). This correspondence suggests that listeners are simply uncertain about the target location when a lateral distractor precedes targets near the median plane in the classroom, causing them to guess the target location, which, in turn, causes a bias towards the side. Because this effect depends strongly on SOA (disappearing at long SOAs), it is likely caused by a reduction in sensitivity to target spatial information due to distractor energy, either due to added noise in the representation of target spatial information (e.g., from acoustic interference) or a reduced response to the target cues (e.g., neural suppression of target spatial information, as in the precedence effect).

In both experiments, perceived location of targets located near 45° is biased towards the distractor location, whether the distractor is frontal or lateral (peaks in Fig. 4(A) and dips in Fig. 4(B)). This effect decreases with increasing SOA (i.e., decreases when going from left to right in Figs. 4(A) and 4(B)), which suggests that it is also caused by relatively low-level effects related to the dynamics in the representation of auditory spatial cues.

Biases in spatial representation have been observed previously in behavioral experiments, both in the face of adaptation to a repeated preceding sound (Kashino and Nishida, 1998; Carlile *et al.*, 2001) and in situations involving concurrent stimuli (Best *et al.*, 2005). However, these previous studies generally found that perceived target locations were biased away from rather than towards the distractor location. It is possible that since the distractor and target are identical in the current experiments, they are more likely to be perceived as coming from the same sound source—a source whose perceived location depends on integrating spatial information from both the target and the distractor.[2] Further experiments should test whether stimuli from different directions are more likely to be perceived at some intermediate, integrated location when they are perceptually similar.

Another factor that may play a role in the localization bias of sources at intermediate locations is exogenous allocation of spatial attention, or "orienting" (Spence and Driver, 1994). In particular, the distractor may cause an involuntary shift of spatial attention toward its location, causing subsequent targets from other regions of space to be localized less reliably. Such an explanation is also supported by the observation that the biases were reduced at larger SOAs, where there is sufficient time to disengage attention from the distractor and reorient attention toward the target.

The lateral distractor causes a strong medial bias in responses to nearby targets (shown by the peaks for the far right target positions in the graphs and panels of Fig. 4(B)). However, in contrast with all of the effects discussed above, this effect is essentially independent of SOA for the values used in this study and occurs in both the classroom and the anechoic room. Such a lack of dependence on the details of the stimulus attributes (e.g., SOA, the level of reverberation in the environment) suggests that the nature of this bias is very different from the biases already considered. In particular, such an effect is unlikely to be caused by low-level interactions, which should become weaker with increasing SOA and should be affected by the level of reverberant energy in the environment. Instead, it is likely that this effect is caused by a more central mechanism, such as a change in the response strategy employed by the listener. For instance, for lateral targets (where localization is relatively poor), subjects may use the distractor as a perceptual "anchor," judging target location relative to the distractor location rather than in absolute coordinates (Hartmann and Rakerd, 1989; Litovsky and Macmillan, 1994; Recanzone *et al.*, 1998). Such a strategy may have caused subjects to overestimate the separation between the target and distractor, resulting in the observed bias. Although there was no corresponding bias for frontal targets in the frontal-distractor runs, employing relative judgments may not be an efficient strategy for localizing sources near the medial plane, where spatial auditory resolution can be an order of magnitude better than for sources to the side (Mills, 1958). The idea that subjects may alter their response strategy based on specific knowledge about the possible stimulus locations has been explored in several previous experiments, and substantial effects on localization response patterns were observed (Perrett and Noble, 1995).

Another important finding in this study was that the listeners' responses changed during the course of the experimental runs in a way that depended on the location of the distractor presented in that run. The resulting contextual bias caused responses to consistently be displaced away from the distractor location. To our knowledge, this is the first example of short-term (on the scale of minutes) spatial auditory plasticity induced without either visual feedback (Jack and Thurlow, 1973; Warren *et al.*, 1981; Recanzone, 1998) or a near-continuous exposure to a constant (adapting) auditory stimulus (Thurlow and Jack, 1973; Kashino and Nishida, 1998; Carlile *et al.*, 2001). This effect may be either bottom up, driven purely by the statistical distribution of the stimuli heard within a run (45% of which were coming from the distractor location), or top down, driven by the listener's knowledge of the distractor location and attempts to direct spatial attention away from it.[3]

Finally, it is important to note that although several potential accounts for the localization biases observed have been explored above, there may be other possibilities. Importantly, however, given the large differences in how the various effects varied with attributes such as SOA and environment, it is clear that no one mechanism can explain all of the effects observed.

V. SUMMARY AND CONCLUSIONS

Localization of a target click was affected by the presence of a preceding click in a number of different ways, over SOAs much larger than are typically thought to cause interstimulus interactions. Given the complex pattern of observed effects, several forms of distractor-target interaction, operating at different stages in the spatial auditory processing pathway, likely contribute to how a target is localized in runs containing distractors:

- In the reverberant classroom (but not in anechoic space), response variability and response bias are larger when sources are near the median plane and preceded by a lateral distractor (as opposed to the frontal distractor). This effect is particularly strong at short SOAs (up to 100 ms). The observed reduction in localization accuracy and reliability suggests that, under these conditions, listeners cannot access spatial information in the target. This effect is likely caused by some combination of acoustic interference between distractor and target and ongoing neural suppression of later-arriving target location information by the preceding distractor and its subsequent reflections.
- Perceived locations of targets at intermediate angles are biased towards the distractor in both environments, an effect that disappears with increasing SOA. This effect appears to be the result of interactions in the neural representation of space or of exogenous orienting caused by the distractor.
- The lateral distractor repulses nearby sources in both environments, independent of SOA. This effect is likely more central, e.g., from listeners adopting a "relative" rather than "absolute" localization strategy.
- A contextual bias occurs both in trials with and without a distractor, causing a shift in the perceived locations of the targets in the frontal-distractor runs compared to the lateral distractor runs. This bias is consistently away from the distractor position in the run and builds up over the course of minutes. The contextual bias may be caused by either bottom-up or top-down factors.

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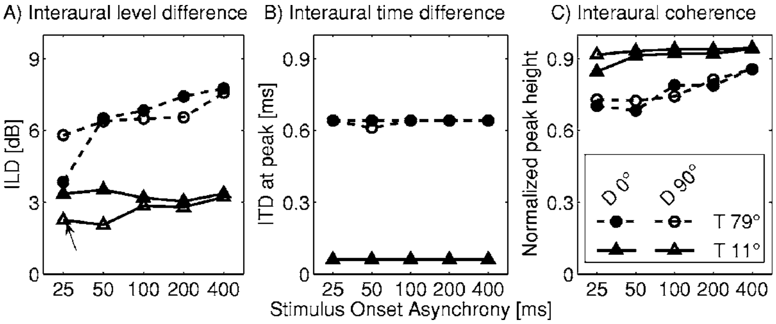

FIG. 6. Analysis of the acoustic effect of the distractor on the target for four combinations of the distractor/target locations, plotted as a function of the SOA. A) Interaural level difference. B) Interaural time difference (ITD) determined as a delay corresponding to the peak in the broadband interaural cross correlation. C) Height of the peak of the interaural cross correlation. The arrow indicates the condition in which the largest bias in the classroom, but not in the anechoic room, was observed.

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APPENDIX: ACOUSTIC ANALYSIS OF REVERBERANT STIMULI

Binaural recordings of several stimulus pairs used in the behavioral experiments in the classroom were obtained using a KEMAR manikin. A manikin with microphones fit in its ear canals (Etymotic Research ER 11 attached to a DB-100 Zwislocki Coupler) was placed on the chair in the center of the loudspeaker setup with its ears at approximately the level of the human subjects' ears. Signals from distractor/target pairs were recorded and digitized using a SR785 Dynamic Signal Analyzer. The digitized signals were then transferred to a PC for analysis. Four distractor/target stimulus pairs were chosen (distractor 0°/target 11°, distractor 0°/target 79°, distractor 90°/target 11°, and distractor 90°/target 79°), representing two distractor locations and targets both near to and far from the distractor positions. Recordings were made for SOAs of 25 and 400 ms, while results for other SOAs (50, 100, and 250 ms) were simulated from the 400 ms recording by shifting the target portion of the recording appropriately in time.

The recordings were analyzed to examine any consistent effects of the distractor (and its reflections) on the interaural parameters (interaural level differences or ILDs, interaural time differences or ITDs, and interaural coherence) present during the onset of the direct sound from the target.

ILD values were estimated by taking a 20 ms window, starting at the onset of the target click, and calculating the overall intensity difference in dB between the left and right ear signals using the formula $\mathrm{ILD}=20\times(\log_{10}\mathrm{rms}_{\mathrm{right\ ear}}-\log_{10}\mathrm{rms}_{\mathrm{left\ ear}})$. The onset of the target click was estimated from the recording by finding the first sample at which the signal passed a threshold (set by eye to be just above the level of the reverberant tail of the distractor). Panel A of Fig. 6 shows that the ILD is approximately 3 dB for targets located at 11° and ranged between 4 and 8 dB for targets located at 79°. The distractor reduced this ILD in an SOA-dependent matter in three out of the four spatial configurations (i.e., the ILD magnitude was smallest at the shortest SOAs).

The most prominent localization bias caused by a preceding distractor was an attraction of frontal targets by the lateral distractor for short SOAs in the classroom (solid lines in Fig. 4(B)). Analysis shows that the ILD is smaller for this configuration than ILD observed at longer SOAs (see the open triangle in panel A that is marked by the arrow). If anything, such a decrease in ILD magnitude predicts a localization bias *towards* the median plane, opposite the observed behavioral bias. Thus, the large lateral bias of frontal targets in the presence of a lateral distractor cannot be explained by distractor-induced changes in ILD.

ITD was estimated by calculating the normalized, running broadband interaural cross correlation of the left and right ear signals using a 5 ms analysis window with 0.6 ms cosine-squared ramps. Panel B of Fig. 6 plots the time delay at which the peak of the cross-correlation function occurs, and panel C plots the height of this normalized cross-correlation peak. Panel B shows that the ITD is approximately 640 μs for the target at 79° and approximately 60 μs for the target at 11°. There is no significant change in the ITD corresponding to the cross-correlation peak with changes in SOA, suggesting that the localization biases observed in the room were not due to shifts in the dominant ITD (a result consistent with previous analysis of how spatial cues are affected by reverberant energy; see Shinn-Cunningham *et al.*, 2005). However, the distractor reduced the interaural coherence of the target, an effect that decreased systematically with increasing SOA, especially for lateral targets (consider the open and filled circles in panel C, which increase from left to right).

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[1] If all subjects show similar patterns of results, but differ in the overall magnitude of an effect, the standard deviation in the mean taken across subjects will tend to overestimate the variability in the results and underestimate the reliability of the observed effects. Such subject differences are automatically taken into account in many statistical techniques (e.g., in repeated-measures ANOVA analysis) in order to improve the power in the test. One way of accounting for differences is to only analyze changes in observations within subject, thereby reducing the across-subject variation (e.g., compare error bars in Figs. 2 and 4). However, such a representation makes it difficult to compare overall size of an effect. An alternative approach is to plot data using within-subject rather than across-subject standard deviations to show the reliability of the observed effects. Conceptually, plotting data in this way is identical to subtracting off overall differences in subject performance prior to computing the variability within a particular experimental condition. Practically speaking, such a representation is identical to assuming a statistical linear model in which each subject and each condition have effects (e.g., analogous to the assumptions in a repeated-measures ANOVA). Mathematically, the within-subject standard error of the mean can be computed as follows. Let X_{ij} denote the observations obtained for subject i observed in condition j, where each

condition corresponds to a particular, unique combination of the levels of the factors in an experiment (using this terminology, each experiment reported here had seven target lateralities ×6 SOA conditions ×2 distractor locations=84 conditions). For example, if analyzing standard deviations in responses, X_{12} corresponds to the standard deviation obtained for subject 1 in condition 2, where condition 2 denotes a particular combination of target azimuth, SOA, and distractor location. Let $\bar{X}_i$ represent the mean of the observations for subject i averaged across all (84) conditions, and let $\bar{X}$ represent the grand mean (i.e., the average across all subjects and all conditions). To account for between-subject differences in overall performance, individual differences in subject performance are removed by computing $Y_{ij}=X_{ij}-\bar{X}_i+\bar{X}$. By construct, the across-subject mean of Y_{ij} is equal to the across-subject mean of X_{ij}. However, the observations Y_{ij} remove the average difference between the observations for subject i and the grand mean by subtracting off $\bar{X}_i-\bar{X}$. The standard error of the mean of Y_{ij} gives the within-subject variability. As an example, the error bars in Fig. 5 use the within-subject standard errors, computed as described here. The (across-subject) standard errors of the mean are, on average, 1.59 times larger.

[2] Perceptual integration of target and distractor spatial information is likely to become stronger as the spatial separation of the distractor and target decreases (and it is more likely that the listener perceives distractor and target as coming from the same source at a fixed location). However, instead of growing stronger as the target location approaches the distractor location, the attraction observed here disappears. A possible explanation is that other factors come into play when target and distractor are close, counteracting the expected integration of spatial information.

[3] Given the presence of the contextual bias in the perceived target locations it would also be useful to know how the distractor location was perceived. This location was not measured directly. Listeners were highly familiar with the experimental setup and always knew the exocentric location of the distractor (both visually and by hearing an example). Although listeners were instructed to ignore the distractor and to only judge target location, casual reports from the listeners suggested that they were always aware of the distractor location during a run, both because they knew where the distractor would be within the run and because they heard multiple presentations coming from the distractor location within the run (i.e., on 83% of the trials). However, given the contextual bias observed in target localization, there is a reasonable chance that the perceived/memorized location of the distractor also shifted throughout a run. For instance, if the contextual bias is caused by a uniform shift in some internal neural representation of space (as suggested by the constant size of the shift seen in Fig. 3(A)), the perceived distractor location may have shifted in the same direction as the target. Alternatively, if the contextual bias caused by the repeated presentation of the distractor in a run occurs because listeners adopt the strategy of attending away from the distractor, the perceived distractor location may shift in the opposite direction. These possibilities could be tested by directly measuring the perceived distractor location throughout a run. However, whether or not the perceived location of the distractor itself shifted during an experimental run, the current results show that the repeated presentation of a distractor caused a number of systematic changes in how target stimuli were localized.

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