Reverberation enhances onset dominance in sound localization

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Temporal variation in sensitivity to sound-localization cues was measured in anechoic conditions and in simulated reverberation using the temporal weighting function (TWF) paradigm [Stecker and Hafter (2002). J. Acoust. Soc. Am. **112**, 1046–1057]. Listeners judged the locations of Gabor click trains (4 kHz center frequency, 5-ms interclick interval) presented from an array of loudspeakers spanning 360° azimuth. Targets ranged ±56.25° across trials. Individual clicks within each train varied by an additional ±11.25° to allow TWF calculation by multiple regression. In separate conditions, sounds were presented directly or in the presence of simulated reverberation: 13 orders of lateral reflection were computed for a 10 m × 10 m room (RT_{60}≊300 ms) and mapped to the appropriate locations in the loudspeaker array. Results reveal a marked increase in perceptual weight applied to the initial click in reverberation, along with a reduction in the impact of late-arriving sound. In a second experiment, target stimuli were preceded by trains of "conditioner" sounds with or without reverberation. Effects were modest and limited to the first few clicks in a train, suggesting that impacts of reverberant pre-exposure on localization may be limited to the processing of information from early reflections.
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I. INTRODUCTION

Numerous classic and contemporary studies have demonstrated the importance of sound onsets in spatial hearing. The precedence effect, for example, illustrates listeners' propensity to localize in the direction of earliest arriving among successive identical sounds (Wallach *et al.*, 1949; Blauert, 1971; Litovsky *et al.*, 1999; Brown *et al.*, 2015), as does the Franssen effect (Franssen, 1962; Hartmann and Rakerd, 1989; Whitmer, 2004) for extended tones. Binaural discrimination is similarly dominated by the onsets of tones (Stecker and Bibee, 2014; Diedesch and Stecker, 2015), noise bands (Houtgast and Plomp, 1968), and rapid trains of clicks (Hafter and Dye, 1983; Hafter *et al.*, 1983; Stecker and Brown, 2010) or noise bursts (Freyman *et al.*, 1997, 2010). Onsets even dominate the simple localization (Stecker and Hafter, 2002) and lateralization (Stecker *et al.*, 2013) of high-rate periodic sounds. These studies span a wide range of stimuli, spatial cues, and psychophysical approaches, and suggest that onset dominance is a fundamental property of spatial hearing.

Why do onsets play such an important role in spatial hearing? A widely held view is that because sound onsets are not contaminated by their own echoes and reverberation (i.e., they arrive at the listener's position first), they provide the only unambiguous spatial cues available in reverberant listening. This view is particularly evident in discussions of the precedence effect—which has sometimes been explicitly termed "echo suppression" (Clifton, 1987; Yang and Grantham, 1997; Krumbholz and Nobbe, 2002)—but has also been extended to explain the role of envelope fluctuations in ongoing sound, e.g., the "ongoing precedence effect" (Freyman *et al.*, 2010; Nelson and Takahashi, 2010; Dietz *et al.*, 2013). Yet nearly all studies of onset dominance have been conducted in laboratory environments completely lacking realistic echoes or reverberation: typically, localization has been assessed in free-field (anechoic) conditions, while lateralization and discrimination have been studied using earphone presentations. Thus, onset dominance is suggested to be an adaptation to reverberant listening that persists even under non-reverberant conditions. It is thus unknown whether current measures accurately estimate the importance of sound onsets in everyday reverberant listening. The current study adopts the temporal-weighting function approach of Stecker and Hafter (2002) to directly measure the influence of onsets and ongoing cues on sound localization in anechoic and carefully simulated reverberant[1] conditions.

Some literature on the precedence effect suggests that onset dominance is not a fixed property of spatial hearing, but rather is modified by the recent listening context. In the "buildup of precedence effect" (Clifton, 1987), stronger precedence effects are observed following repeated exposure to a consistent pseudo-echoic context than for probe stimuli presented in isolation or following an inconsistent context. One interpretation of the buildup effect is that the auditory system adapts to changes in the reverberant environment (e.g., upon moving from an office to a hallway) in order to most appropriately suppress echoic information (Freyman *et al.*, 1991; Clifton *et al.*, 1994; Chang and Freyman, 1998; Freyman and Keen, 2006), possibly in a cue-specific way (Djelani and Blauert, 2001; Krumbholz and Nobbe, 2002;

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Brown and Stecker, 2013). Similarly, a wide range of recent studies demonstrates that exposure to a consistent reverberant context can help the auditory system compensate for the perceptual effects of reverberation (Watkins and Makin, 2007; Watkins *et al.*, 2011; Brandewie and Zahorik, 2010, 2013; Zahorik *et al.*, 2012). A second aim of the current work is to investigate whether pre-exposure to a reverberant or non-reverberant context ("buildup") similarly alters the temporal weighting of spatial information in reverberant or free-field sound localization.

II. EXPERIMENT 1: TEMPORAL WEIGHTING OF SOUND LOCALIZATION CUES IN ANECHOIC AND REVERBERANT SPACE

Experiment 1 (Exp. 1) employed the procedure of Stecker and Hafter (2002) to measure temporal weighting functions (TWFs) for sound localization in the anechoic free field (thus replicating the earlier study) and in moderate simulated reverberation (modeling a 10 m × 10 m room with $RT_{60} \approx 300$ ms).

A. Methods

Experiments were conducted at Vanderbilt University Medical Center, Nashville TN. All procedures, including recruitment, consenting, and testing of human subjects followed VUMC guidelines and were reviewed and approved by the cognizant Institutional Review Board. Experimental and analytical methods were based on those of Stecker and Hafter (2002). As in that study, and detailed below, listeners localized brief click trains that were presented with independent variation in the azimuth of each click. Multiple regression of judgments onto individual click azimuths was used to derive perceptual weights, which comprise the TWFs.

1. Participants

Eight normal-hearing adult listeners participated in the experiment. One was the second author (participant 0514) and two (0509, 0515) were lab members who were experienced with spatial listening tests but not informed of the purpose or hypotheses of the study. Others were paid participants naive to the purpose of the experiment. All participants demonstrated normal hearing as confirmed by pure-tone detection thresholds <15 dB hearing level (HL) over the range 250–8000 Hz.

2. Stimuli

Stimuli were trains of 4-kHz Gabor clicks as in Stecker and Hafter (2002). As illustrated in Fig. 1(a), each train

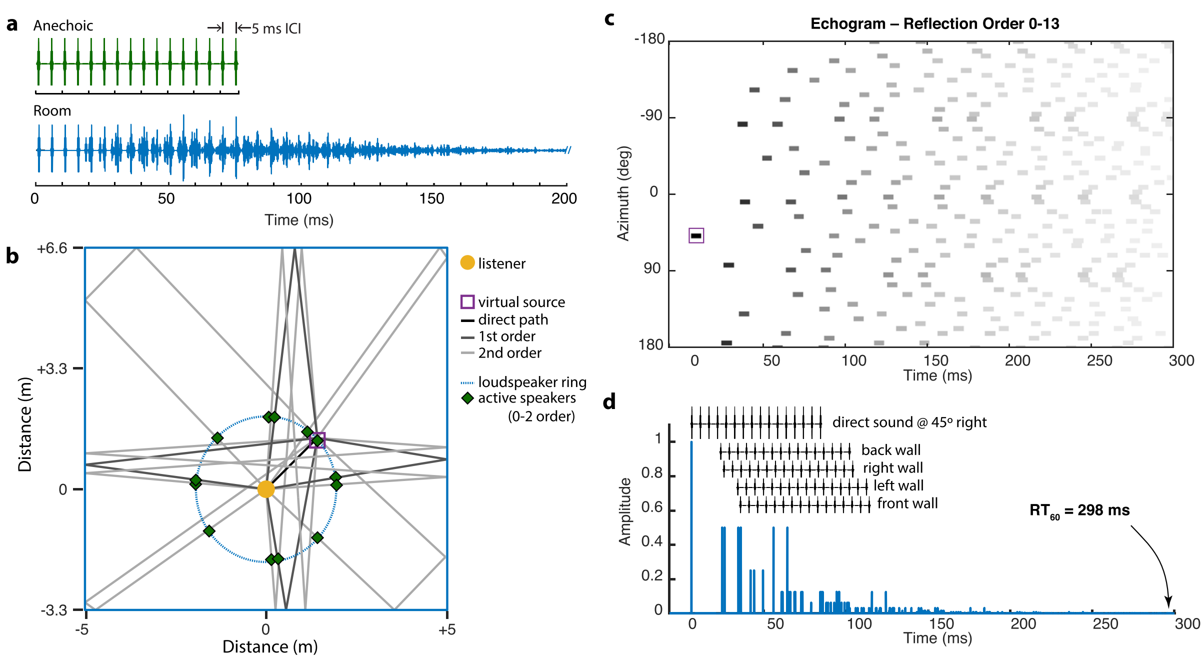

FIG. 1. (Color online) Stimulus generation. (a) Stimuli were trains of 16 Gabor clicks with 4 kHz carrier frequency and 5-ms ICI, presented from a 360° azimuthal array of ear-height loudspeakers (64 speakers spaced every 5.625°) at 2 m distance. In separate conditions, clicks were presented from single loudspeakers (Anechoic, upper panel) or were convolved with a spatial RIR (Room, lower panel). Each waveform in (a) plots the monaural sum across loudspeaker channels for a source at +45° right azimuth. (b) Room conditions presented virtual reflections of order 1–13, simulating the front, back, and side walls of a 10 m × 10 m room (solid blue lines). Dotted blue line indicates the ring of physical loudspeakers. Direct, first-, and second-order reflected sound paths (black and gray lines) are illustrated for a virtual sound source at +45° right azimuth (violet square). Reflection azimuths were rounded to the nearest physical loudspeaker (green diamonds) for presentation. (c) Spatial echogram illustrates the timing (horizontal axis), azimuth (vertical axis), and intensity (gray shading; no scale) of simulated reflections—i.e., the RIR—for a virtual source at +45° right azimuth (direct sound indicated by violet square). Plot is truncated at 300 ms post onset but low-intensity reflections continue until 392 ms. (d) Summed echogram plots the amplitude (vertical) of reflections in (c) as a function of arrival time. Exponential decay due to absorption ($\alpha = 0.5$) results in 60-dB reverberation time (RT_{60}) of approximately 300 ms. Copies of the stimulus waveform (inset) are plotted on the same temporal scale to illustrate the timing of first-order early reflections, which arrive 17–34 ms after the direct sound (i.e., after click 4). Note that click trains are illustrated as if presented from a single common azimuth; in the actual experiment, target stimuli presented subsets of clicks from a range of source azimuths spanning ±11.25° with reflections computed separately for each source.

presented 16 clicks (nominal duration 2 ms each) at an inter-click interval (ICI) of 5 ms, for a total duration of 77 ms. Sounds were computed in MATLAB (Mathworks, Natick, MA), synthesized at 48 kHz and presented via a dedicated Dante audio-over-ethernet network (Focusrite Rednet, El Segundo, CA) including digital amplification (Ashly ne8250PE, Webster, NY) and discrete loudspeakers (Meyer MM-4, Berkeley, CA) at 70 dB sound pressure level (SPL) peak level.

On each trial, a target stimulus was presented at a "base" azimuth value, θ, which ranged $\pm 56.25°$ in $11.25°$ steps. By convention, $0°$ indicates the frontal midline, with negative azimuths to the left and positive values to the right. Base values were presented an equal number of times (6 per run), in random order. Within each trial, individual clicks i were presented randomly from one of five loudspeakers centered on θ and separated by $5.625°$, as in Stecker and Hafter (2002). Thus, the azimuth of each click, θ_i, ranged from $\theta - 11.25°$ to $\theta + 11.25°$.

In "room" conditions, stimuli were presented with simulated lateral reflections corresponding to the front, back, and side walls of a 10 m × 10 m room [Fig. 1(b)]. The image method (Allen and Berkley, 1979) was used to compute the azimuths (rounded to the nearest loudspeaker direction), delays, and amplitudes (wall absorption $\alpha = 0.5$) of direct sound and reflections of the 1st through 13th order. Note that floor and ceiling reflections were not simulated (i.e., floor and ceiling $\alpha = 1.0$). The resulting room impulse response [(RIR), Fig. 1(c)] included reflections arriving 17–392 ms after direct sound, and reverberation time of $RT_{60} \approxeq 300$ ms.

Each source stimulus was convolved with the RIR to compute a waveform for each of the 64 loudspeakers. This was done separately for each of the five source locations ($\theta \pm 0°$, $5.625°$, $11.25°$) selected on each trial. The results were summed across sources for simultaneous playback across all 64 physical loudspeakers.

3. Procedure

Testing took place in the Vanderbilt Bill Wilkerson Center Anechoic Chamber Laboratory (ACL). The ACL consists of a large ($4.6 \times 6.4 \times 6.7$ m) anechoic chamber (Eckel Industries, Cambridge, MA). Participants were seated in the center of a 2-meter (radius) loudspeaker array, consisting of 64 ear-height loudspeakers spanning 360° azimuth (spacing of 5.625°). A touch-sensitive display (Apple iPad Air, Cupertino, CA) was mounted on a boom a few inches above the participant's lap and displayed a top-down schematic of the room and loudspeaker array.

On each trial, listeners were instructed to face forward while a single stimulus was presented and then indicate the perceived location of the stimulus by touching the display at the corresponding location. Listeners were instructed to make an immediate eye movement to the judged position in the loudspeaker array, make note of the location, and finally record the foveated location on the schematic diagram. This instruction was intended to encourage listeners to rapidly orient to the sound's location and not perseverate on the scaling judgment. Following each response, listeners were instructed to return to initial position before the next trial began. Head position was monitored via closed-circuit video. Listeners completed 66 trials per run (6 trials per base azimuth value θ) and repeated eight runs per condition. Conditions were tested in random order within each of the eight replicate blocks.

4. Analysis

Response data were transformed to ranks (i.e., ranked according to lateral position) within each run prior to weighting analysis. This step minimized response nonlinearities and distributional differences across runs and subjects. Perceptual weights for each of the 16 clicks in a train were then estimated by multiple linear regression of the rank-transformed response θ_R onto the azimuth values of individual clicks (θ_i), using MATLAB

$$\hat{\theta}_R = \sum_{i=1}^{16} \beta_i \theta_i + k. \quad (1)$$

For comparison across subjects and conditions, regression coefficients β_i were then normalized so that absolute values sum to 1 over the 16-click stimulus duration.

$$w_i = \frac{\beta_i}{\sum_{j=1}^{16} |\beta_j|}. \quad (2)$$

The normalized weights w_i comprise the TWF and indicate each click's relative influence on a listener's judgments. Typically, weights vary between 0 (no influence) and 1 (a perfect linear relationship). Strongly negative values would indicate a biasing of judgments *away* from the click location. TWFs were estimated separately for each combination of listener and stimulus condition using data obtained in all runs for that combination.

a. Dominance of onset and offset cues. As in our previous studies (Stecker *et al.*, 2013; Stecker, 2014), onset and offset dominance were quantified by the *average ratio* [(*AR*), Saberi, 1996]. *AR* was defined as the ratio of onset (first click) or offset (final click) weight to the mean of intermediate weights (i.e., the mean excluding onset and offset clicks),

$$AR_{onset} = \frac{w_1}{\sum_{i=2}^{N-1} w_i/(N-2)}, \quad (3)$$

or

$$AR_{offset} = \frac{w_N}{\sum_{i=2}^{N-1} w_i/(N-2)}, \quad (4)$$

where N ($= 16$) indicates the total number of clicks in each train. AR_{onset} quantifies the dominance of binaural cues carried by the initial/onset burst. AR_{offset} similarly indicates the relative influence of the final, offset, burst.

Statistical tests comparing weights to the null hypothesis that $w_i = 1/16$ for all i were computed by 5000-fold bootstrap

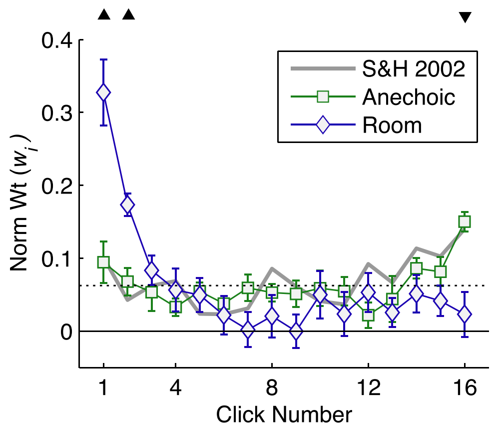

FIG. 2. (Color online) Group-mean TWF for anechoic (green squares) and room (blue diamonds) conditions of Exp. 1. TWFs plot mean normalized weight, w_i, ± standard error (s.e.) for each of 16 clicks. Dotted line indicates reference value (1/16) that would obtain if all clicks were equally weighted. Symbols at top indicate significant weight differences between anechoic and room conditions, as obtained from paired bootstrap difference test (two-tailed $p < 0.05$): upward-pointing triangles indicate significantly greater weight in the room than anechoic condition, and vice-versa for downward-pointing triangles. Thick gray line: anechoic TWFs obtained by Stecker and Hafter (2002) in nearly identical conditions (4 kHz Gabor click trains at 5-ms ICI; clicks span $\theta \pm 11°$ azimuth with 5.5° loudspeaker spacing; mean of 2 listeners).

tests across listeners (Fox, 2008). Similarly, pairwise differences in weights or *AR* across conditions were evaluated by paired bootstrap tests on the difference scores. The proportion of difference scores less than zero gave the raw p value. A two-tailed p value was generated for each comparison by taking the minimum of p or $1-p$, or 0.0002 if $p = 0$.

B. Results and discussion

Figure 2 plots the mean TWFs obtained in Exp. 1. Individual data are plotted in Fig. 3. Anechoic TWFs (green) closely matched those previously reported for 4-kHz trains at 5-ms ICI (Stecker and Hafter, 2002, gray line in Fig. 2), revealing only modest onset dominance ($w_1 = 0.094$, which was not significantly greater than 1/16: $p = 0.1$) but more robust recency effects (Stecker and Hafter, 2009) in the form of significant weights on clicks 14 and 16 [$p < 0.05$ indicated by asterisks (*) in Fig. 3]. Compared to the anechoic data, weights obtained in the room condition were significantly greater on clicks 1–2 and significantly lower on click 16 (all $p < 0.05$).

The *AR* quantifies the degree of onset and offset dominance in TWFs. Results for Exp. 1 are plotted as open symbols in Fig. 4. Measured this way, significant onset dominance ($AR_{onset} > 1.0$) was observed in all conditions, but was significantly stronger in the room condition ($AR_{onset} = 7.8$) than in the anechoic condition ($AR_{onset} = 1.9$, $p < 0.0002$ via bootstap difference test). A significant difference in the opposite direction was found for AR_{offset} (0.7 versus 2.8, $p < 0.0002$).

Whether assessed in terms of *AR* or of the weights themselves, onset dominance was 3–4 times stronger when stimuli were presented in simulated reverberation than anechoically. The mechanism of this difference is presumably related to acoustical interference during the later portion of the stimulus, as can be appreciated from Figs. 1(a) and 1(d). Nevertheless, it suggests that previous TWF measurements in the free field (Stecker and Hafter, 2002) and using earphones (Stecker *et al.*, 2013) may significantly underestimate the degree of onset dominance experienced during real-world listening.

In contrast, the weighting of clicks near sound offset was significantly reduced by reverberation, presumably due to acoustic interference by temporally overlapping reflections. This suggests that recency effects (Stecker and Hafter, 2009; Stecker *et al.*, 2013) and offset weighting (Stecker, 2014) might be specific to anechoic listening in which late-arriving sound is unambiguously associated with the source direction (cf. Chang and Freyman, 1998).

One final aspect of the room TWFs should be noted: in both the group average and the individual TWFs, weights decreased in an approximately monotonic fashion following click 1. In contrast, previous reports of anechoic TWFs have noted immediate reductions in post-onset weights such that click 2 received among the smallest weights. Based on that pattern, Stecker and Hafter (2002) argued against power-law adaptation of binaural sensitivity as proposed by Hafter and Buell (1990) and in favor of a role for onsets *per se*. The room TWFs of the current study are rather more consistent with a gradual reduction in binaural effectiveness, at least over the first several clicks (i.e., those arriving before or alongside the first few early reflections).

III. EXPERIMENT 2: EFFECTS OF REVERBERANT PRE-EXPOSURE

The results of Exp. 1 suggest a strong influence of reverberation on TWFs for sound localization. Experiment 2 (Exp. 2) investigated the impact of pre-exposing listeners to the reverberant or anechoic context prior to presentation of a target stimulus. Previous studies suggest two competing

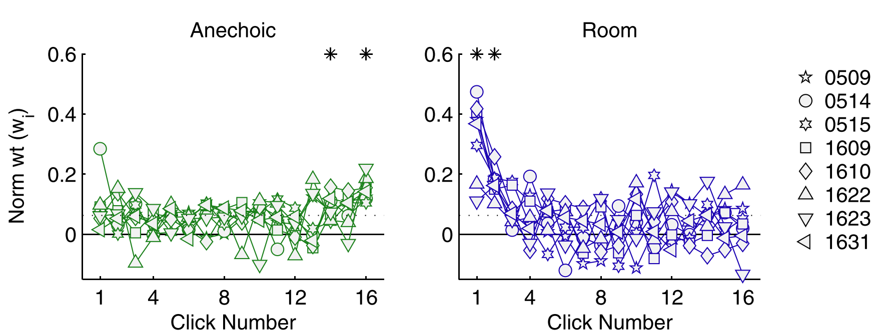

FIG. 3. (Color online) Individual TWFs for anechoic (left panel; green symbols) and room (right panel: blue symbols) conditions in Exp. 1. Symbols plot data for individual subjects (legend at far right). Asterisks (*) at top indicate weights significantly greater than 1/16 (one-tailed bootstrap test, $p < 0.05$). Other formatting as in Fig. 2.

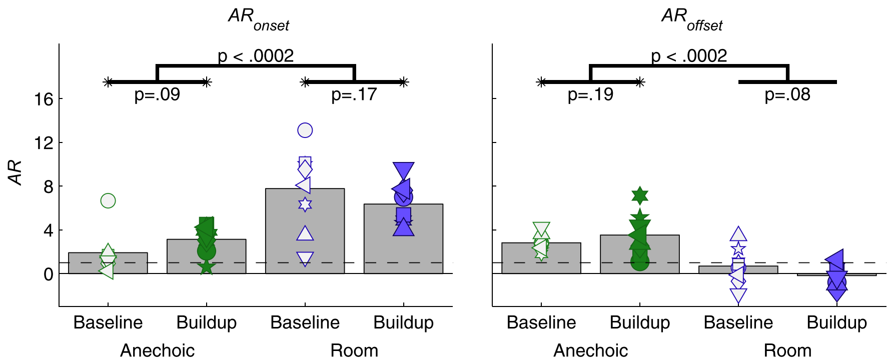

FIG. 4. (Color online) *AR* values for onset (left) and offset (right) weights across conditions. In each panel, bars plot mean *AR* values across listeners. Symbols plot individual values (legend in Fig. 3). Baseline measures for anechoic (leftmost bar, open green symbols) and room (third bar, open blue symbols) conditions of Exp. 1 differed significantly in each case, with significantly greater AR_{onset} and smaller AR_{offset} in room than anechoic conditions ($p < 0.0002$ indicated by horizontal lines at top of each plot). That statistical difference between room and anechoic conditions was repeated in buildup conditions of Exp. 2 (second and fourth bars, filled symbols). Neither AR_{onset} nor AR_{offset} differed significantly between buildup and baseline conditions (p values indicated below each cross bar). Dashed line indicates $AR = 1.0$ as expected for equal weighting of all clicks. Asterisks (*) indicate conditions with $AR > 1.0$ (one-tailed $p < 0.05$).

hypotheses for this manipulation. First, the literature on buildup of precedence effects (Freyman *et al.*, 1991; Yang and Grantham, 1997; Brown and Stecker, 2013) suggests stronger suppression of post-onset ("lag") clicks following exposure to a consistent context. In that case one would expect stronger onset dominance following pre-exposure, possibly in both anechoic and room conditions. Second, the literature on reverberant pre-exposure in speech perception (Watkins and Makin, 2007; Brandewie and Zahorik, 2010) suggests that pre-exposure should reduce the perceptual effects of reverberation; i.e., it should reduce weights on click 1 and increase weights on later clicks in the room condition.

A. Methods

Procedures for Exp. 2 were identical to those of Exp. 1 with the exception that target stimuli were preceded by a series of "conditioner" stimuli (Freyman *et al.*, 1991) meant to pre-expose listeners to the reverberant or anechoic context.

1. Participants

The same subjects participated in both Exp. 1 and Exp. 2.

2. Stimuli

Target stimuli were identical to those of Exp. 1. In Exp. 2, however, each target was preceded by a series of 12 conditioner stimuli, which were identical to target stimuli except that all clicks shared a common source azimuth (θ) of 0°. Conditioners were separated from one another by 300-ms interstimulus intervals (ISI). A 500-ms ISI separated the final conditioner from the target stimulus. "Room" conditioners were convolved with the appropriate RIR (thus pre-exposing listeners to the simulated room), whereas "anechoic" conditioners were presented from a single loudspeaker.

3. Procedure

Procedures were identical to Exp. 1. Listeners were instructed to listen to the conditioner stimuli, but base their localization judgments on the targets alone.

B. Results and discussion

Figure 5 plots TWFs measured in buildup conditions (filled symbols) alongside baseline TWFs measured in Exp. 1. Overall, there were no large and significant differences between buildup and baseline weights. Anechoic TWFs included significant weights on click 16 in both buildup and baseline conditions. Click 1 weights in the anechoic buildup condition significantly exceeded the null hypothesis value of 1/16 ($w_1 = 0.151$, $p < 0.0002$) but not the baseline value ($w_1 = 0.094$). Room TWFs were also similar across buildup and baseline conditions: clicks 1 and 2 received significant weight in both conditions. Significant weights were also found on clicks 3 and 4 in the buildup case. Significant pairwise differences were confined to clicks without obvious ties to the hypotheses under test (clicks 4, 10, and 14 in the anechoic case and click 6 in the room case).

AR measures for buildup TWFs (Fig. 4) tell a similar story. As in Exp. 1, both measures differed significantly between anechoic and room conditions ($AR_{onset} = 3.1$ vs 6.23, respectively, $p < 0.0002$; $AR_{offset} = 3.5$ vs -0.2, $p < 0.0002$). No *AR* measures differed significantly between baseline (Exp. 1) and buildup (Exp. 2).

The results thus provide little direct evidence that pre-exposure alters onset dominance in a significant way. There are, however, features of the data that suggest more subtle or specific effects, and these may be worth considering given how poorly we understand the mechanisms of reverberant pre-exposure. These issues are taken up in the general discussion.

In the absence of evidence to the contrary, we are left to conclude that onset dominance in sound localization is markedly less affected by pre-exposure to anechoic or reverberated sound than other perceptual features such as speech perception (Watkins and Makin, 2007; Brandewie and Zahorik, 2010) or source-echo fusion (Freyman *et al.*, 1991). In that regard, the results appear roughly consistent with past comparisons of buildup effects across fusion and spatial judgments. Yang and Grantham (1997) and Brown and Stecker (2013) reported significantly stronger buildup effects for fusion than for binaural discrimination and lateralization, respectively.

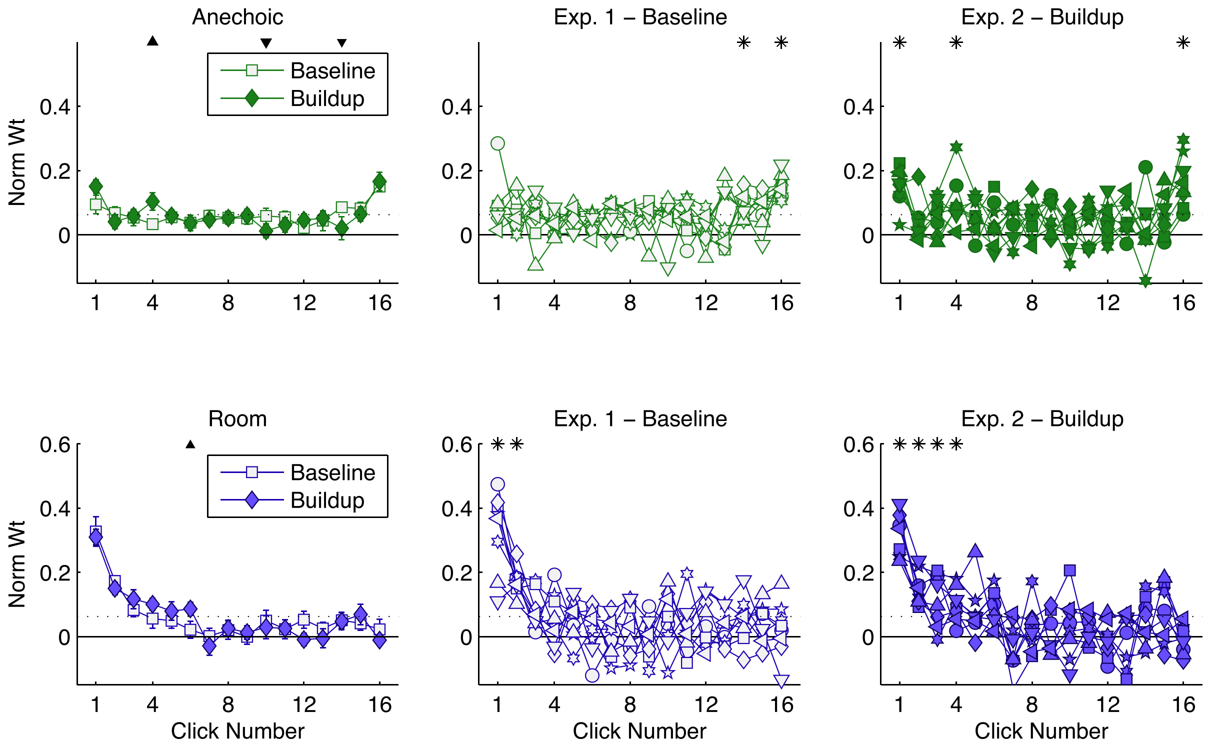

FIG. 5. (Color online) Temporal weighting functions obtained in buildup conditions (Exp. 2, filled symbols) compared to baseline conditions (Exp. 1, open symbols). Top panels (green) plot data for anechoic condition; lower panels (blue) plot data for room condition. In each row, the left panel plots group-mean TWFs as in Fig. 2. Triangle symbols at top indicate significant weight differences between conditions: upward-pointing triangles indicating greater weighting in buildup than baseline condition (two-tailed bootstrap test, $p < 0.05$) and vice-versa for downward-pointing triangles. Center and right panels plot TWFs for individual subjects as in Fig. 3. Asterisks (*) at top indicate weights significantly greater than 1/16 (one-tailed bootstrap test, $p < 0.05$).

IV. GENERAL DISCUSSION

A. Enhanced onset dominance in reverberation

The clearest finding of this study is the 3–4 fold increase in onset dominance for targets presented in simulated reverberation. That difference is similar in magnitude to the effect of reducing the ICI from 5 to 2 ms, a stimulus configuration that is strongly dominated by onset cues (Stecker and Hafter, 2002; Stecker *et al.*, 2013). The current results suggest that past studies underestimated the degree of onset dominance in real-world listening and bolster the view that spatial hearing relies inordinately on such features (Stecker, 2016).

B. Limited influence of pre-exposure to anechoic or reverberant context

In contrast to the clear impact of reverberation on onset dominance, TWFs measured following pre-exposure hardly differed from baseline conditions. It could be that sound localization is robust to pre-exposure effects in a way that perceptual fusion and speech understanding are not. Alternatively, the effects of pre-exposure might be limited to specific features not captured by the broad hypotheses motivating this study. Two aspects of the data may be worth considering in that regard:

First, considering the anechoic conditions, although pairwise comparisons were not themselves significant, significant click 1 weights (w_1) were observed in buildup but not in baseline conditions. The pattern of mean weights is consistent with the buildup of precedence effect, particularly when comparing weights across clicks 1 and 2 as in precedence studies of click pairs (Shinn-Cunningham *et al.*, 1993). The ratio w_1/w_2 increased from 1.4 at baseline to 3.7 in buildup conditions [$w_1/(w_1+w_2)=0.58$ vs 0.79, see Stecker and Hafter, 2002, Fig. 3]. That difference seems comparable to buildup effects reported with click pairs, in that buildup can extend echo thresholds by a factor of 2–3 or more [see Brown *et al.*, 2015, Fig. 4(B)]. To our knowledge, however, no studies have directly quantified buildup in terms of changes to source/echo weights, nor have any measured buildup with more than 2 clicks.

Second, considering the room conditions, note that one significant pairwise weight difference was observed at click 6 (i.e., roughly 25 ms post onset). An accompanying trend for higher weights on clicks 3–5 suggests the possibility that pre-exposure slightly enhanced listeners access to spatial cues arriving 10–25 ms post onset. That time range is noteworthy because it overlaps the *initial time delay gap* (Beranek, 1962), which separates direct sound from first-order early reflections arriving 17–34 ms later (see Fig. 1). A possible effect of pre-exposure could be to reveal this gap—during which direct sound can be reliably accessed—or to calibrate the interval during which early reflections reinforce rather than compete with the spatial impression of sound (Bradley and Soulodre, 1995).[2]

Each of these observations suggests a plausible impact of pre-exposure that is consistent with prior findings. While tantalizing, however, the evidence is not strong. Future studies should aim to replicate or disconfirm these effects.

C. Limitations of the study

Although the effects reported here appear robust, there are several limitations that should be considered, particularly with respect to the null result of pre-exposure. The first is that the conditioner stimuli were presented only from the front (0° source azimuth) and did not vary from trial to trial or click to click in the manner that target stimuli did. The purpose was to expose listeners to the overall room simulation but not to other spatial aspects of stimuli on each trial. Yet perceptual differences between conditioners and targets, or between the spatial arrangement of early reflections, could have reduced the effectiveness of pre-exposure.

Second is the choice to study a single room configuration and orientation. It remains unknown whether results vary across environments with different geometry, reverberation time, or complexity. Similarly, the use of a single type of narrowband test stimulus with a fixed carrier frequency and ICI potentially limits the applicability of results to other more naturalistic stimuli.

Note that the loudspeaker configuration precluded simulation of floor and ceiling reflections. Instead, the room simulation focused on lateral reflections (front, back, and side walls), which are likely to be the most important for azimuthal localization. Including floor and ceiling echoes would increase the reverberation time similarly to changing the absorption coefficient (omitting floor and ceiling echoes is equivalent to setting $\alpha = 1.0$ for those surfaces) but would not meaningfully alter the azimuthal geometry of reflections.

Finally, the range of individual differences observed in the data, although not atypical, suggests that different listeners might adopt different strategies, particularly with respect to how they process contextual information within and across trials. In particular, we note that participant 0514, the second author and an experienced binaural listener, exhibited the greatest onset dominance in baseline conditions of Exp. 1, but not in buildup conditions of Exp. 2. While a thorough investigation of these matters is beyond the scope of this study, they could be addressed in future studies.

V. SUMMARY AND CONCLUSIONS

(1) **Reverberation enhances onset dominance in sound localization.** Listeners relied more heavily on the spatial characteristics of early clicks when localizing sound in a simulated moderately reverberant room. This suggests that previous measures of onset dominance in anechoic and headphone listening may have underestimated the importance of onsets in real-world (i.e., reverberant) listening.

(2) **Reverberation reduces recency effects in sound localization.** Whereas anechoic conditions replicated the importance of late-arriving sound for localization (Stecker and Hafter, 2009), such effects were entirely absent in room conditions. That is, late-arriving cues are masked or distorted by the room response, such that their importance is probably limited to cases where such cues remain salient and unambiguous (i.e., anechoic listening).

(3) **Limited influence of pre-exposure ("buildup") on anechoic localization.** Preceding the target stimulus with a series of conditioner stimuli did not dramatically increase onset dominance in localization, supporting arguments that buildup of the precedence effect relates primarily to the perceptual fusion of sources and echoes rather than their spatial percepts (Brown and Stecker, 2013).

(4) **Limited influence of reverberant pre-exposure on localization.** Similarly, pre-exposing listeners to the reverberant context produced only subtle changes to temporal weighting in reverberant localization. In particular, pre-exposure did not reduce onset dominance to anechoic levels or otherwise compensate for the perceptual effects of reverberation (Watkins and Makin, 2007; Brandewie and Zahorik, 2010). A modest trend in the data suggests that effects of pre-exposure might be limited to enhancement of spatial cues prior to and during the first few early reflections, but requires confirmation in future studies.

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[1]Throughout this paper, the term "reverberation" is used in a general sense to refer to the entire room response. This includes both *early reflections* and the late diffuse response (*reverberation per se*) that emerges as reflections densely overlap in time.

[2]Also note the low weight on click 7, which occurs around the time that first-order reflections arrive from the front wall. Integrating the frontal echo should pull the image toward center and reduce the localization weight, whereas integrating the earlier side reflections should pull the image away from center and increase the weight. That this happens to a greater extent following pre-exposure is an interesting possibility that should be replicated and followed up in future studies.

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