Dynamic-range compression affects the lateral position of sounds

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Dynamic-range compression acting independently at each ear in a bilateral hearing-aid or cochlear-implant fitting can alter interaural level differences (ILDs) potentially affecting spatial perception. The influence of compression on the lateral position of sounds was studied in normal-hearing listeners using virtual acoustic stimuli. In a lateralization task, listeners indicated the leftmost and rightmost extents of the auditory event and reported whether they heard (1) a single, stationary image, (2) a moving/gradually broadening image, or (3) a split image. Fast-acting compression significantly affected the perceived position of high-pass sounds. For sounds with abrupt onsets and offsets, compression shifted the entire image to a more central position. For sounds containing gradual onsets and offsets, including speech, compression increased the occurrence of moving and split images by up to 57 percentage points and increased the perceived lateral extent of the auditory event. The severity of the effects was reduced when undisturbed low-frequency binaural cues were made available. At high frequencies, listeners gave increased weight to ILDs relative to interaural time differences carried in the envelope when compression caused ILDs to change dynamically at low rates, although individual differences were apparent. Specific conditions are identified in which compression is likely to affect spatial perception.
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I. INTRODUCTION

Sound localization is an important function of the healthy auditory system, helping listeners to stay safe in their physical environment and orient themselves toward objects of interest. However, preservation of sound-localization abilities has traditionally not been a primary goal in the design of hearing aids and cochlear implants. Dynamic-range compression has been identified as one type of signal processing routinely used in modern hearing devices that potentially has deleterious effects on spatial hearing (e.g., Byrne and Noble, 1998; Ricketts *et al.*, 2006). Synchronizing compression at the two ears, as is done in some recently introduced hearing aids incorporating wireless technology, may alleviate such effects (Sockalingam *et al.*, 2009; Kreisman *et al.*, 2010). However, few detailed studies on this question have been published, and it appears that the nature and severity of the impact of compression on spatial hearing is yet to be fully resolved. The present study examined how compression acting independently at each ear affects the perceived lateral position of sounds for normal-hearing listeners. By identifying particular conditions in which compression is most likely to affect spatial perception, the findings may help to guide the design and evaluation of new compression algorithms for use in hearing devices that aim to preserve spatial-hearing abilities.

Dynamic-range compression aims to reduce the wide range of sound levels occurring in the natural environment to a narrower range that better matches the capability of the impaired ear (Villchur, 1973). To achieve this, level-dependent amplification is provided: more gain is provided to low-level signals and less gain to high-level signals. Thus compression continually adjusts the sound level. When compression operates independently at each ear, the relative level at the two ears is also adjusted, and so interaural level differences (ILDs) are altered. ILDs are one of the two primary cues used for sound localization in the horizontal plane, the other being interaural time differences (ITDs) (Middlebrooks and Green, 1991). In the case of a single sound source in the free field, compression will generally act to reduce any naturally occurring ILD (Byrne and Noble, 1998), and so, after compression, the ILD may suggest a more central location than the sound source's true location.

Previous studies have found the impact on spatial hearing of compression applied independently at each ear to be rather small. Musa-Shufani *et al.* (2006) demonstrated that compression does worsen discrimination of ILDs but has no effect on ITD discrimination. The impact on ILDs was greater for higher compression ratios and shorter attack times and followed a similar pattern for normal-hearing and hearing-impaired listeners. However, Musa-Shufani *et al.* found the impact of compression to be small in a related virtual source-identification experiment assessing horizontal-plane localization performance. This was attributed in part to the dominant contribution from low-frequency ITDs (Wightman and Kistler, 1992). Keidser *et al.* (2006) similarly found no significant effect of compression on the horizontal-plane localization performance of bilateral hearing-aid wearers, although average performance was marginally worse with multi-channel wide-dynamic-range compression compared to a reference linear amplification scheme.

Relatively little is known about how front-end compression in cochlear implants affects spatial hearing, although the impact is potentially large as most users of bilateral cochlear implants are thought to rely primarily on ILDs for sound localization (van Hoesel and Tyler, 2003; Seeber and Fastl,

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2008). In a pilot study, Ricketts *et al*. (2006) found that some bilateral cochlear-implant users appeared to localize sounds more accurately with the front-end compression in their devices deactivated. However, in a later study (Grantham *et al*., 2008), most subjects localized sounds more accurately with front-end compression activated even though the compression, which acted independently at each ear, had been shown separately to worsen ILD discrimination. The poorer performance with compression deactivated may have been due to a confounding effect, however: sounds were presented at a lower level in this condition, leading subjects to comment that the stimuli sounded soft and muffled.

One factor that may have contributed to the surprisingly small impact of compression on localization found in previous studies is the way in which performance was quantified. Generally, an overall error measure was calculated, averaged across all test directions. However, as compression is assumed to affect localization by altering ILDs, it can be expected that the severity of the effect will be related to the size of the naturally occurring ILD before compression. ILDs are nominally zero for a source in the median plane and grow (non-monotonically) for sources toward the side of the listener (Feddersen *et al*., 1957). As such, it is possible that a substantial impact of compression on the localization of lateral sources may have been partially concealed by the absence of any effect for sources closer to the median plane. A further consideration is the limited range of stimuli used in these studies. It is well established that listener weighting of binaural cues varies with the spectral and temporal characteristics of the stimulus (Wightman and Kistler, 1992; Macpherson and Middlebrooks, 2002; Seeber, 2007), and the practical behavior of a compressor is also heavily stimulus dependent (Stone and Moore, 1992; Verschuure *et al*., 1996; Kates, 2010). It follows that any impact of compression on spatial hearing is likely to depend strongly on stimulus characteristics.

Hearing-device compression is a dynamic process in which the gain is continually adjusted in response to changes in input level. When compression is applied independently at each ear, it is possible for dynamic ILD changes to be generated. Dynamic changes in ILD can be followed as lateral movement if the rate of change is sufficiently low, less than about 5 Hz (Blauert, 1972; Grantham, 1984). Furthermore, because only ILDs are principally affected, compression introduces conflict between ITDs and ILDs. Previous studies with normal-hearing listeners have shown that when ITDs and ILDs are out of their natural combinations, listeners sometimes perceive multiple auditory images (e.g., Hafter and Jeffress, 1968; Gaik, 1993; Seeber, 2007). Previous studies have not addressed in detail the dynamic aspects of changes to binaural cues generated by compression nor the potential effects of conflict between cues.

The present study aimed to address these issues by investigating in detail the impact of compression on binaural cues and the perceptual consequences of the processing. A variety of sounds were spatialized using head-related transfer functions (HRTFs), processed using fast-acting dynamic-range compression operating independently at each ear and presented to normal-hearing listeners over headphones. Listeners judged the lateral position of the resulting auditory event and reported if a moving or split image was perceived. The test stimuli were processed with HRTFs corresponding to a source at either -60° or $+60^\circ$ azimuth. The expectation was that without compression, listeners would hear a single, stationary image at a lateral position corresponding to one of these two directions. Deviations from this response to uncompressed sounds, either in terms of perceived lateral position or the occurrence of moving or split images, indicate an effect of compression on spatial hearing.

II. METHODS

A. Participants

Eleven normal-hearing participants took part in the experiment (eight females, three males, mean age = 25 years, range: 20–34 years), all having audiometric thresholds $\leq$ 20 dB HL at octave frequencies between 125 and 8000 Hz. Except for two participants who were members of the research group, participants had limited experience in psychoacoustic studies related to spatial hearing. The study was approved by the Ethics Committee of the School of Psychology at the University of Nottingham. Participants were paid for their attendance.

B. Equipment

Stimuli were generated and processed using MATLAB (The MathWorks). Signals were transferred digitally from a computer sound card to a custom-built, calibrated headphone amplifier with 24-bit digital-to-analog converters, and presented through Sennheiser HD 600 headphones. Participants sat in a sound-isolated booth and entered their responses using a trackball device.

C. Stimuli

Seven different stimuli were used (Table I). These included speech and a range of artificial stimuli designed to test the effect of onset/offset rate, ongoing envelope modulation, and the timing of pulses relative to the compressor time constants. The SPEECH stimulus comprised a single sentence ("They moved the furniture") taken from the IHR Sentence List (Macleod and Summerfield, 1990). Each artificial stimulus was constructed from a broadband (200 Hz to 8 kHz) pink noise burst (NB) to which various forms of envelope modulation were applied. The SAM NB stimulus was created by sinusoidally amplitude modulating (SAM) the NB at a rate of 4 Hz. This rate was chosen because natural speech contains a broad peak in its modulation spectrum close to this frequency (Houtgast and Steeneken, 1985). Three pulse-train (PT) stimuli comprising short (3 ms duration + 1 ms Gaussian rise/fall) pulses were generated from the NB. For LONG IPI PT, the inter-pulse interval (IPI) of 100 ms was chosen to be longer than the nominal release time of the compressors (60 ms, see Sec. II D), whereas for SHORT IPI PT, the IPI was 30 ms, equal to half the release time. SLOW ONSET PT also had an IPI of 30 ms but with the addition of 250 ms Gaussian-shaped overall onset and offset ramps. The remaining two stimuli, SLOW

TABLE I. Details of the stimuli used in the experiment.

Label	Description	Overall onset/offset	Ongoing envelope modulation	Duration (ms)[a]
SLOW ONSET NB	Noise burst with gradual onset and offset	250 ms Gaussian rise/fall[b]	—	1800
SLOW ONSET PT	Pulse train with gradual onset and offset	250 ms Gaussian rise/fall	Pulse train: 3 ms pulses[c] +1 ms rise/fall, 30 ms IPI	1800
FAST ONSET NB	Noise burst with abrupt onset and offset	10 ms Gaussian rise/fall	—	1000
SAM NB	Sinusoidally amplitude modulated noise burst	—	Sinusoidal amplitude modulation: 4 Hz rate, 100% depth	1000
LONG IPI PT	Pulse train with longer inter-pulse interval (IPI)	—	Pulse train: 3 ms pulses +1 ms rise/fall, 100 ms IPI	1000
SHORT IPI PT	Pulse train with shorter inter-pulse interval (IPI)	—	Pulse train: 3 ms pulses +1 ms rise/fall, 30 ms IPI	1000
SPEECH	"They moved the furniture." Male talker.	—	—	1400

[a]Total duration including any overall onset and offset time.
[b]Rise/fall times were measured between the 10% and 90% points of the envelope amplitude.
[c]Pulse duration was measured as the time for which the envelope amplitude exceeded the 67.5% point.

ONSET NB and FAST ONSET NB, had overall Gaussian-shaped onset and offset ramps of 250 and 10 ms, respectively; no ongoing envelope modulation was applied to these stimuli. Fresh noise samples were generated for each trial. These stimuli formed the input to subsequent signal processing stages that are described in the following section. All stimuli were presented to the input of these processing stages at a simulated level of 65 dB SPL (root-mean-square level for the sentence; steady-state level of the pink noise before envelope application).

D. Signal processing

The stimuli were convolved with non-individualized HRTFs to simulate a source in the frontal horizontal plane at an azimuth of $-60°$ or $+60°$. A single HRTF set from the AUDIS catalogue was used ("moe," Blauert *et al.*, 1998). The same HRTF set was used throughout to ensure that the binaural cues present in the sounds, and the effect of compression on those cues, did not vary between participants. The HRTF set was equalized for use with diffuse-field-equalized headphones, and the headphones used in the present study were also diffuse-field equalized. No attempt was made to compensate for variations in the headphone transfer function on individual listeners.

The resulting signal at each ear was split into a low- and a high-frequency channel with a crossover between the channels at 2 kHz. This filtering was performed using 256-tap linear-phase finite impulse response filters to avoid phase distortion. The stop-band attenuation of the filters was at least 55 dB, and the two channels had a flat magnitude response when combined. The pure delay introduced by the filters was compensated for. All processing was performed at a sampling rate of 44.1 kHz.

No further processing was performed in the low-frequency channel. In three different conditions, the high-frequency channel was left unprocessed or subjected to either dynamic-range compression or imposition of a static bias in interaural level difference:

(1) *Unprocessed condition*. This condition served as a control as listeners were presented with undisturbed binaural cues.
(2) *Dynamic compression condition*. Dynamic-range compression was applied in the high-frequency channel independently at each ear as would be the case in a traditional bilateral hearing-device fitting without wireless synchronization between devices. The compressors were set to provide fast-acting wide-dynamic-range compression: compression ratio 3:1, compression threshold 30 dB SPL within the high-frequency channel, attack time 5 ms, and release time 60 ms. Attack and release time were defined as in ANSI S3.22 (ANSI, 2003). These parameters are representative of those used in modern hearing aids providing "syllabic compression" with the amount of compression applied at high frequencies being toward the upper end of what might be prescribed for a mild hearing loss (e.g., Moore *et al.*, 2010).
(3) *Static ILD bias condition*. A fixed ILD bias was imposed over the duration of the sound, equivalent in magnitude to that nominally induced by 3:1 compression in steady-state conditions. This condition was included to test the importance of the dynamic nature of hearing-device compression as opposed to the presence of conflicting binaural cues *per se*. The magnitude of the ILD bias was calculated separately for each stimulus so as to reduce the long-term ILD (in dB) in the high-frequency channel by a factor of three.

Several factors guided the decision to apply the processing in the high-frequency channel only. In a simplified manner, this configuration reflects the fact that more compression is often required at high frequencies than at low, for example, in the common case of a sloping high-frequency hearing loss. The greatest effects of compression on spatial hearing were also anticipated with the compressors operating at high frequencies where naturally occurring ILDs are larger. Finally, by leaving the low-frequency channel unprocessed, it was possible to assess the benefit of undisturbed low-frequency binaural cues to normal-hearing listeners. The use of open-fitting hearing aids may allow some hearing-impaired individuals access to undistorted low-frequency cues (Noble *et al.*, 1998).

The processing applied in the dynamic compression and static ILD bias conditions reduced the overall level in the high-frequency channel. Make-up gain was therefore applied to restore the original balance between low and high frequencies. The amount of make-up gain was calculated separately for each stimulus as the gain needed to restore the long-term root-mean-square level in the high-frequency channel after processing to the same level as in the unprocessed condition. The level matching was based on a combined level at the left and right ears, calculated on the basis of energy summation (i.e., for a sound with zero ILD, the combined level was 3 dB greater than the level at either ear alone). Because the same amount of make-up gain was applied at both ears, this process did not affect ILDs.

The experiment included two bandwidth conditions: (1) A high-pass condition in which the high-frequency channel, complete with any processing that had been applied, was presented to listeners in isolation and (2) a full-bandwidth condition in which the high-frequency channel was recombined with the unprocessed low-frequency channel and listeners were presented with the resulting full-bandwidth signal. The use of these two bandwidth conditions allowed us to directly assess the impact of distortion to high-frequency binaural cues while also investigating the potentially ameliorating effect of having access to undisturbed low-frequency cues.

All sounds were amplified to a comfortable listening level of approximately 60 dB SPL before being presented to listeners, and level roving ($\pm$4 dB in 2 dB steps) was implemented across trials to ensure that overall level was not a reliable cue for the type of processing applied. Amplification and level roving was applied symmetrically at the two ears to avoid any further changes to ILDs.

E. Lateralization task

A line-dissection method was used to measure the perceived lateral position of the auditory event. A horizontal line, terminated by vertical strips labeled "left ear" and "right ear," was shown on a display screen. Participants moved a marker along this line using a trackball to indicate the perceived lateral position within the head. The left-ear termination was assigned a value of -1 and the right-ear termination $+1$. All lateralization data in this manuscript are presented in the units of this dimensionless response scale. If sounds were externalized (i.e., perceived "outside the head"), participants were instructed to project the perceived location on to the interaural axis. Similar line-dissection methods have been used in other lateralization studies in which externalization of some or all stimuli could not be expected (e.g., Yost, 1981; Seeber, 2007; Seeber and Hafter, 2011).

Rather than providing a single response that described the overall position of the auditory event, participants were instructed to indicate, in separate runs, its leftmost and rightmost extents. Data were collected in this way to reveal whether compression might have other effects on the lateralization of sounds beyond a simple shift in apparent position. It was explained to participants that in the case of a single, focused sound image, the leftmost and rightmost extents would likely coincide, while in the case of a diffuse, moving, or split image, the leftmost and rightmost extents may differ. On each trial, the listener's task was twofold. After first positioning the marker to indicate the leftmost or rightmost extent (according to the "task instruction" for the current run), the listener then had to choose one of three response options that best described the nature of what they heard: (1) a single, stationary image (whether focused or diffuse); (2) a moving or gradually broadening image; or (3) more than one image (i.e., an image split occurred).

F. Procedure

For each combination of the seven different stimuli, the two simulated directions ($-60°$ and $+60°$), the three high-frequency-channel processing conditions (unprocessed, dynamic compression, and static ILD bias), and the two bandwidth conditions (high-pass and full-bandwidth), each participant performed five trials in which the instruction was to indicate the leftmost extent and five trials in which the instruction was to indicate the rightmost extent. This gave a total of 840 test trials for each participant.

Additionally, each participant performed 160 dummy trials, interleaved with the main test trials, in which the sound was presented from a direction of $-45°$, $-30°$, $-15°$, $0°$, $+15°$, $+30°$, or $+45°$, selected at random. Stimulus type, bandwidth condition, and task instruction were also chosen randomly for dummy trials, while the high-frequency channel was always unprocessed. Inclusion of the dummy trials ensured that participants experienced sounds across a full range of lateral positions.

The experiment was split into eight runs of 125 trials with each run taking about 10 min. Trials were presented in random order with the constraint that the task instruction was fixed throughout individual runs to avoid confusion. A reminder of the task instruction and the three available response options remained visible on a second display screen throughout the experiment.

Before data collection began, the experimenter explained the task and the three response options to the participant with the aid of a series of diagrams. Participants were asked to focus on the lateral position of the auditory event in deciding which response option to use and not to judge other qualities of the sounds. A practice session comprising 100 trials was run to familiarize participants with the task. No feedback was given, although the experimenter verbally confirmed with the participant that they understood the task and the meaning of the three response options before proceeding to the main experiment.

G. Data analysis

1. Combining left- and right-hemisphere trials

Left–right symmetry was assumed *a priori* and so responses to sounds presented at a simulated azimuth of −60° were pooled with responses to matching sounds presented at a simulated azimuth of +60°. To combine results from the two sides, for all left-hemisphere trials, the sign of the raw lateralization response was inverted and the task instruction was swapped; that is, trials in which the original instruction was to indicate the leftmost extent ("leftmost trials") became "rightmost trials," and vice versa. Thus all data are presented on a scale between zero (center of the head) and one (fully lateralized toward the ear on the side of the simulated sound source).

2. Midpoint and span measures

After combining trials from the left and right hemispheres, two summary measures were calculated separately for each participant: (1) midpoint—the arithmetic average of the median leftmost extent and the median rightmost extent, representing the "center" of the auditory event; and (2) span—the absolute difference between the median rightmost extent and the median leftmost extent, representing the diffuseness of the image, the amount by which it moved, or the lateral separation between split images.

Because the test stimuli (−60° or +60° simulated azimuth) were generally lateralized toward the ends of the constrained response scale (i.e., were close to being fully lateralized), the raw data were arcsine transformed prior to calculating midpoint and span. The transform was similar to that often used when analyzing proportional data, such as percentage correct scores in a speech identification task, to obtain a scale in which the variance is unrelated to the size of the mean (Studebaker, 1985). In the present study, the aim was to obtain a scale in which span did not vary merely as a result of the overall region of the response scale in which the image was lateralized. The transform had minimal effect across the majority of the response scale but effectively "stretched" the scale for responses close to either ear.

III. RESULTS

A. Core lateralization results

Core lateralization results are presented in Fig. 1. In the unprocessed condition, all test stimuli were lateralized toward the side of the head (values typically around 0.7–0.9) as expected given the simulated source azimuth of ±60°. Most unprocessed sounds were seemingly well focused, typically having a small lateral extent of about 0.15 units. The lateral extent was slightly greater (about 0.25 units) for SLOW ONSET NB and SLOW ONSET PT, the two stimuli that featured a slow overall onset and offset. These stimuli were often reported as "moving/gradually broadening," even in the unprocessed condition (see Sec. III C).

Lateralization responses differed in the dynamic compression and static ILD bias conditions compared to the unprocessed condition. In the high-pass condition, there was a clear tendency for the image to be shifted toward the center of the head in both processed conditions. In the static ILD bias condition, both the left- and rightmost extents were

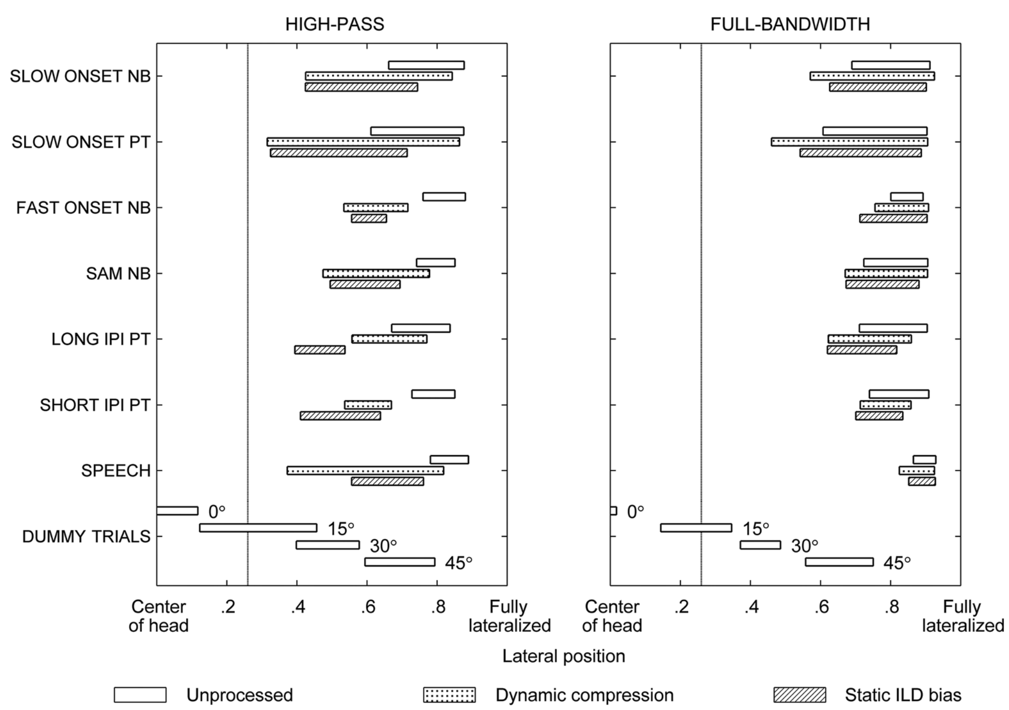

FIG. 1. Core lateralization results for the high-pass (left) and full-bandwidth (right) conditions, for sounds presented at a simulated azimuth of ±60°. Boxes range from the median of the reported leftmost extents of the auditory event to the median of the rightmost extents across all pooled responses (referred to the right hemisphere). The horizontal axes cover the range from the center of the head to a fully lateralized position. The dashed vertical lines are indicative of the average position suggested by the steady-state compressed interaural level difference in the high-frequency channel. Also shown are the dummy-trial results (averaged across all stimuli) for unprocessed sounds presented from simulated source azimuths between 0° and 45°.

typically shifted by a similar amount, indicating an overall shift of the image location. The amount by which the image shifted was reasonably similar for all stimuli and was about 0.2 units. The dashed vertical line indicates the average position suggested by the steady-state compressed ILD in the high-frequency channel (see the Appendix for details); note that the image always remained on the outer side of this line, and so never shifted as far toward the center as would be predicted from the 3:1 reduction in ILD if this was the only salient cue.

For some stimuli, most notably FAST ONSET NB and SHORT IPI PT, responses in the high-pass condition were similar in nature in the dynamic compression and static ILD bias conditions (i.e., the entire image was shifted toward the center of the head). In contrast, for other stimuli (e.g., SLOW ONSET NB, SLOW ONSET PT, and SPEECH), responses differed substantially between the dynamic compression and static ILD bias conditions. For these stimuli, in the dynamic compression condition, the innermost extent shifted toward the center, but the outermost extent generally remained close to its original position (cf. responses in the unprocessed condition). Consequently, the overall lateral extent of the auditory event was considerably increased, covering over half of one side of the head (over 0.5 units) in the case of SLOW ONSET PT.

Lateralization responses in the full-bandwidth condition followed a broadly similar pattern, although differences between the three processing conditions were much less pronounced than in the high-pass condition. Accordingly, the magnitude of any shift toward the center of the head in the dynamic compression and/or static ILD bias condition was markedly smaller.

In addition to the main test conditions, Fig. 1 shows results from the dummy trials in which unprocessed stimuli with natural binaural cues were presented from a range of simulated azimuths. These data demonstrate a monotonic relationship between the simulated source azimuth and the perceived lateral position of the auditory event. The dummy-trial data also suggest that, in general, the image was slightly more focused in the full-bandwidth condition (average lateral extent of 0.15 units) than in the high-pass condition (0.25 units): this likely reflects the availability of low-frequency cues, including fine-structure ITDs, in the full-bandwidth condition, which were absent in the high-pass condition.

B. Effects of processing condition on midpoint and span

The midpoint and span measures were used to quantify the differences between processing conditions. Figure 2 shows the distributions of midpoint and span across participants for each experimental condition. A decrease in midpoint represents a shift in lateral position toward the center of the head. An increase in span may represent either increased diffuseness of the image, lateral movement, or a split into two images, depending on how the sound was perceived.

Differences between processing conditions were assessed using non-parametric statistical tests. In each case, two Wilcoxon signed-rank tests were performed, the first comparing the dynamic compression and unprocessed conditions, and the second comparing the static ILD bias and unprocessed conditions. Significant differences from the unprocessed condition ($p < 0.05$, two-tailed, $N = 11$) are indicated by asterisks in Fig. 2 and details are given in Table II. Note that all statistical tests were performed on the values of midpoint and span calculated from the arcsine-transformed data (see Sec. II G 2), but in producing Fig. 2 and Table II, the values have been converted back to the original response scale for ease of interpretation.

The results are consistent with the observations made in relation to Fig. 1. In the high-pass condition, midpoint was always significantly smaller in both the dynamic compression and static ILD bias conditions than in the unprocessed condition, reflecting a shift of the image toward the center of the head. The size of this shift was about 0.2 units on average but was more variable across stimuli for dynamic compression than for the static ILD bias. In the full-bandwidth condition, a significant reduction in midpoint remained for four of the seven stimuli in the static ILD bias condition (SLOW ONSET PT, SAM NB, LONG IPI PT, and SHORT IPI PT), and two in the dynamic compression condition (LONG IPI PT and SHORT IPI PT). The size of the shift was consistently smaller in the full-bandwidth condition, being at most 0.1 units.

In some cases, span was significantly greater in the dynamic compression condition than in the unprocessed condition. In the high-pass condition, there was a significant increase in span of between 0.17 and 0.44 units for SLOW ONSET PT, SAM NB, and SPEECH. An increase in span of similar size for SLOW ONSET NB was narrowly non-significant ($p = 0.067$) because of greater between-subject variability in this condition. Conversely, for SLOW ONSET NB in the full-bandwidth condition, an increase in span of 0.2 units was the only significant effect of dynamic compression on span.

The static ILD bias generally had little effect on span. There was a single case in which span was significantly greater in the static ILD bias condition than in the unprocessed condition (SPEECH stimulus in the high-pass condition). However, the increase in median span (0.16 units) was only about a third as large as the corresponding increase for the dynamic compression condition (0.44 units).

It is evident from Fig. 2 that there was considerable variability across participants in some conditions, more noticeably in span than in midpoint. An important factor contributing to this variability is that Fig. 2 does not take into account which response option was used, and hence data are combined across trials in which listeners may have perceived the sound in a fundamentally different way. Variations in response-option use are addressed in the following subsections.

C. Effects of dynamic compression on response-option use

Figure 3 shows the relative use of the three response options in each experimental condition. In the absence of a straightforward approach to analyzing these categorical data

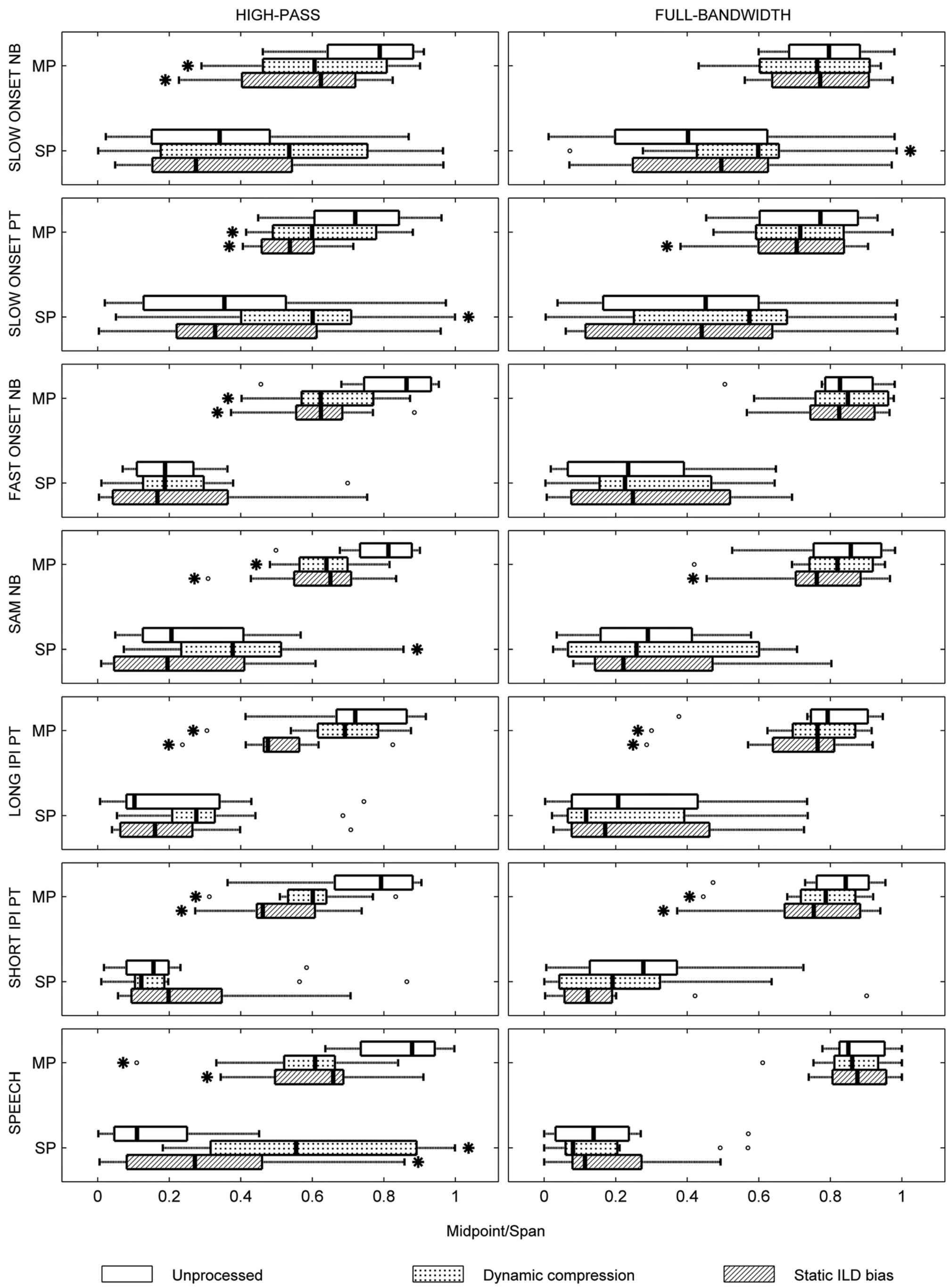

FIG. 2. Distributions of midpoint (MP) and span (SP) across participants in the high-pass (left) and full-bandwidth (right) conditions. Midpoint and span values have been converted back to the original response scale for plotting such that values between zero and one cover the range from the center of the head to a fully lateralized position. Central marks represent the median, boxes indicate the interquartile range (IQR), and whiskers extend to the most extreme data points still within 1.5 IQR of the box edges. Data points lying outside this range are plotted as small open circles. Asterisks indicate a significant difference compared to the unprocessed condition.

obtained in a repeated-measures design, we restrict ourselves to making observational comments on the response-option percentages. In the unprocessed condition, a "single, stationary image" was reported in most trials (typically above 70%) as expected for sounds with undisturbed binaural cues. The percentage of "single, stationary image" trials was, however, lower for SLOW ONSET NB (55% averaged across the high-pass and full-bandwidth conditions) and SLOW ONSET PT (30%). These stimuli were often reported as "moving/gradually broadening" even in the unprocessed condition, which likely accounts for the wider lateral extent that was observed for these stimuli in Fig. 1.

Response-option percentages were similar in the unprocessed and static ILD bias conditions, varying by 12 percentage points at most but typically only by 3–4 points. As such, a static offset in ILD, present throughout the duration of the stimulus, rarely increased the occurrence of moving or split images relative to the unprocessed condition. In contrast,

TABLE II. Significant effects ($p < 0.05$) of dynamic compression or a static ILD bias on midpoint and span. Median values across participants are given for the two processing conditions being compared in each case (along with the difference between these). All values have been converted back to the original response scale for consistency with Fig. 2. Exact p values are also given (Wilcoxon signed-rank tests, two-tailed, $N = 11$).

	Dynamic compression vs unprocessed		Static ILD bias vs unprocessed	
	Midpoint	Span	Midpoint	Span
SLOW ONSET NB				
High-pass	0.61 vs 0.79 (−0.18) $p = 0.010$	—	0.62 vs 0.79 (−0.16) $p = 0.001$	—
Full-bandwidth	—	0.60 vs. 0.40 (+0.20) $p = 0.032$		—
SLOW ONSET PT				
High-pass	0.60 vs 0.72 (−0.12) $p = 0.002$	0.60 vs 0.35 (+0.25) $p = 0.005$	0.54 vs 0.72 (−0.18) $p = 0.001$	—
Full-bandwidth	—	—	0.71 vs 0.77 (−0.07) $p = 0.010$	—
FAST ONSET NB				
High-pass	0.62 vs 0.86 (−0.24) $p = 0.001$	—	0.62 vs 0.86 (−0.24) $p = 0.001$	—
Full-bandwidth	—	—	—	—
SAM NB				
High-pass	0.64 vs 0.81 (−0.17) $p = 0.001$	0.38 vs 0.21 (+0.17) $p = 0.024$	0.65 vs 0.81 (−0.16) $p = 0.001$	—
Full-bandwidth	—	—	0.76 vs 0.86 (−0.10) $p = 0.005$	—
LONG IPI PT				
High-pass	0.69 vs 0.72 (−0.03) $p = 0.005$	—	0.48 vs 0.72 (−0.24) $p = 0.001$	—
Full-bandwidth	0.76 vs 0.79 (−0.03) $p = 0.010$	—	0.76 vs 0.79 (−0.03) $p = 0.002$	—
SHORT IPI PT				
High-pass	0.60 vs 0.79 (−0.19) $p = 0.001$	—	0.46 vs 0.79 (−0.33) $p = 0.001$	—
Full-bandwidth	0.79 vs 0.84 (−0.06) $p = 0.001$	—	0.75 vs 0.84 (−0.09) $p = 0.003$	—
SPEECH				
High-pass	0.61 vs 0.88 (−0.27) $p = 0.002$	0.55 vs 0.11 (+0.44) $p = 0.001$	0.66 vs 0.88 (−0.22) $p = 0.002$	0.27 vs 0.11 (+0.16) $p = 0.032$
Full-bandwidth	—	—	—	—

response-option percentages sometimes varied markedly between the unprocessed and dynamic compression conditions. In the high-pass condition, for SLOW ONSET NB, SLOW ONSET PT, SAM NB, and SPEECH, the proportion of "single, stationary image" responses was on average 30 percentage points lower in the dynamic compression condition than in the unprocessed condition with a corresponding increase in the percentage of "moving/gradually broadening" and/or "split image" responses. For the other stimuli (FAST ONSET NB, LONG IPI PT, and SHORT IPI PT), differences between the unprocessed and dynamic compression conditions were negligible. A similar pattern was observed in the full-bandwidth condition, although differences between the unprocessed and dynamic compression conditions were markedly smaller. In the full-bandwidth condition, the greatest reduction in the proportion of "single, stationary image" responses in the dynamic compression condition was 21 percentage points compared to 57 points in the high-pass condition.

Although it cannot be seen from Fig. 3, where group-average data is plotted, individual listeners were generally consistent in their response-option use. For a given experimental condition (ignoring the side of presentation), on average, individual listeners chose the same response option on 17 of 20 repeated trials (varying from 14 of 20 for the least consistent listener to 18 of 20 for the most consistent).

D. Relationship between lateral position and response-option use

The stimuli for which the percentage of "moving/gradually broadening" and/or "split image" responses was substantially higher in the dynamic compression condition (SLOW ONSET NB, SLOW ONSET PT, SAM NB, and SPEECH) were generally the same as those for which there was a significant increase in span. That is, when dynamic compression increased the occurrence of either moving or split images, the separation between the reported left- and rightmost extents of the auditory event increased also. In contrast, for stimuli that listeners predominantly heard as a "single, stationary image" regardless of processing condition (FAST ONSET NB, LONG IPI PT, and SHORT IPI PT),

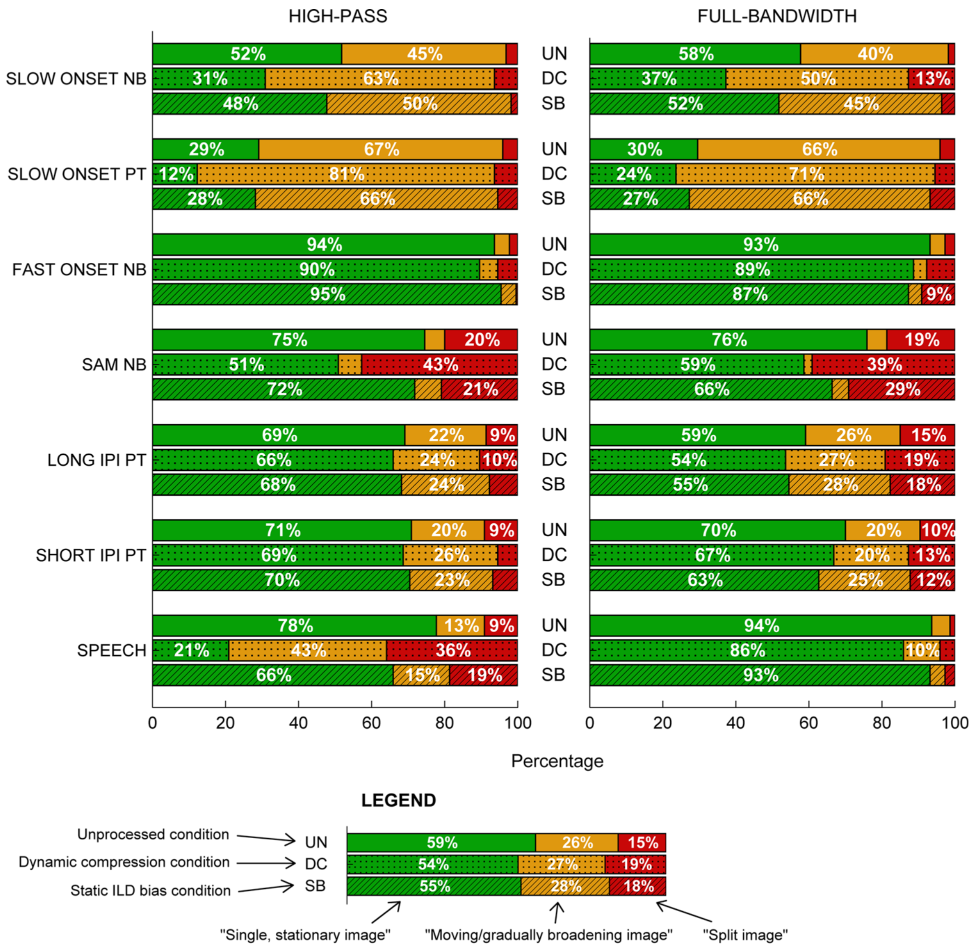

FIG. 3. (Color online) Overall response option percentages in the high-pass (left) and full-bandwidth (right) conditions. In each set of three bars, the upper bar represents the unprocessed condition (UN), the middle bar the dynamic compression condition (DC), and the lower bar the static ILD bias condition (SB). Individual bars are divided into three parts representing the relative frequency of use of each response option: (1) "single, stationary image" (leftmost part); (2) "moving/gradually broadening image" (middle part); and (3) "split image" (rightmost part). The percentages within each bar were derived from a total of 220 trials.

there was no significant increase in span. The results thus show little evidence of increased diffuseness in the event that a single, stationary image was perceived.

Of particular interest are cases in which the proportion of "moving/gradually broadening" and/or "split images" increased substantially in the dynamic compression condition, yet in a considerable number of trials a "single, stationary image" was still reported. Three notable examples are SLOW ONSET NB, SAM NB, and SPEECH, all in the high-pass condition, for which a "single, stationary image" was still reported in 31%, 51%, and 21% of trials, respectively.

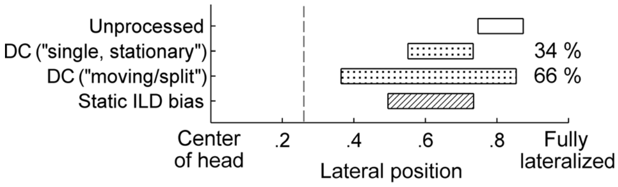

FIG. 4. Lateralization responses in the high-pass condition averaged across the SLOW ONSET NB, SAM NB, and SPEECH stimuli. Results in the dynamic compression (DC) condition are plotted separately for trials in which a "single, stationary image" was reported and trials in which a "moving/gradually broadening image" or "split image" was reported. The percentage of trials in each category is shown. Overall results for the unprocessed and static ILD bias conditions are included for comparison. Boxes extend from the median leftmost extent to the median rightmost extent calculated across all relevant trials (referred to the right hemisphere).

Further analysis revealed that it tended to be the same participants who consistently contributed these "single, stationary image" responses to sounds that were more often perceived as a moving or split image: over half of the "single, stationary image" responses came from just 3 of the 11 participants. Furthermore, individual participants remained fairly consistent in their response-option use from trial-to-trial when considering only these three stimuli in the high-pass condition, choosing the same response option on an average of 16 of 20 repeated trials. The results therefore suggest the presence of individual differences in the processing or weighting of the binaural cues present in these sounds.

Figure 4 shows lateralization data for the high-pass condition averaged across the same three stimuli (SLOW ONSET NB, SAM NB, and SPEECH) and, for the dynamic compression condition, partially broken down by response option. For the 34% of dynamic-compression trials in which a "single, stationary image" was still reported, lateralization responses were similar to those in the static ILD bias condition: The entire image was shifted toward the center of the head by a moderate amount, and there was little increase in its lateral extent. In contrast, for the 66% of dynamic-compression trials in which a moving or split image was reported, the overall lateral extent increased substantially, and it was only the innermost extent that moved toward the center of the head. Thus where there were consistent individual differences in the nature of the percept, these were accompanied by a fundamentally different pattern of lateralization responses.

IV. DISCUSSION

The effect of dynamic-range compression acting independently at each ear on the lateral position of sounds was studied using a variety of virtual acoustic stimuli. In the unprocessed condition, sounds presented from a simulated azimuth of $-60°$ or $+60°$ were lateralized toward the left or right ear, respectively, and the auditory event was generally well focused. When listening only to the processed high-frequency channel, fast-acting compression shifted the image toward the center of the head as did a static ILD bias. In the case of a static ILD bias, the size of the shift was reasonably similar for all stimuli (corresponding to approximately one-fifth of the range between the center of the head and one ear), and there was little increase in the width of the image. The effect of dynamic compression was similar to that of the static ILD bias for stimuli with abrupt onsets and offsets (FAST ONSET NB, LONG IPI PT, and SHORT IPI PT). For stimuli containing more gradual onsets and offsets (SLOW ONSET NB, SLOW ONSET PT, SAM NB, and SPEECH), dynamic compression shifted the innermost extent of the auditory event further toward the center, while the outermost extent remained close to its original uncompressed location; this was accompanied by an increase in reports of "moving/gradually broadening images" and/or "split images." In the full-bandwidth condition, access to undisturbed low-frequency information consistently reduced the severity of any effect of the processing, both in terms of shifts in lateral position and reports of moving or split images.

In the following, the changes to binaural cues introduced by the processing are examined in more detail and related to the lateralization responses. Then an assessment of the relative weighting given to high-frequency binaural cues is made, focusing on the difference between static and dynamic situations. Finally, potential implications for the use of compression in bilaterally fitted hearing devices are discussed.

A. Effects of compression on binaural cues

Here we consider how the natural binaural cues present in the acoustic signals are altered by compression. The primary effect of compression acting independently at each ear on binaural cues is a reduction in ILDs (Byrne and Noble, 1998). Because compression does not, in itself, affect the relative timing at the two ears, ITDs are essentially unaffected, although changes to the envelope shape caused by compression (Stone and Moore, 2007) may conceivably affect the use of time-based cues.

The changes to ILDs caused by the processing were investigated by plotting histograms of short-term ILDs in the high-frequency channel (Fig. 5). ILDs were measured in the experimental stimuli using a single-sided exponential time window with a time constant of 10 ms, after Faller and Merimaa (2004). Comparison of the unprocessed and static ILD bias conditions confirms that the ILD bias reduced an original ILD of about 18 to 6 dB. The peak in the histogram was shifted to a similar value in the dynamic compression condition, and for all stimuli, the average ILD weighted by the signal power in each analysis window ($ILD_{w.a.}$) in the dynamic compression condition was within 2 dB of its value in the static ILD bias condition. Hence the overall reduction in ILD brought about by the dynamic compression was close to the 3:1 reduction nominally suggested by the compression ratio. However, for the stimuli that included gradual onsets and offsets (SLOW ONSET NB, SLOW ONSET PT, SAM NB, and SPEECH), the shape of the ILD histogram was altered by dynamic compression: In some time windows, the short-term ILD was similar to that in the unprocessed condition, and in others, the ILD took intermediate values between those in the unprocessed and static ILD bias conditions. These uncompressed or intermediate ILDs correspond, respectively, to periods in which the level at neither or only one ear was above the compression threshold: When the level at both ears is below the threshold, linear amplification is provided and the ILD is unaltered; when the level at only one ear is above the threshold, the ILD is reduced by an intermediate amount; and when the level at both ears is above the threshold, the ILD is maximally reduced by a factor of three (corresponding to the 3:1 ratio used here).

The occurrence of these uncompressed or intermediate ILDs was quantified as follows: For each stimulus, the highest ILD typically occurring in the static ILD bias condition (represented by the 99th percentile of the distribution) was found. This value is indicated by a dashed vertical line in the relevant middle-panel plot of Fig. 5. Then the proportion of ILDs exceeding this value in the dynamic compression condition was calculated, giving the "proportion of partially compressed ILDs" ($ILD_{p.p.c.}$). $ILD_{p.p.c.}$ is effectively a measure of the extent to which compression caused ILDs to change dynamically during presentation of the stimulus.

Figure 6 shows the median value of the span measure across participants in the dynamic compression, high-pass condition (from Fig. 2) plotted against $ILD_{p.p.c.}$ for each stimulus. The strong correlation ($r = 0.93$) indicates that the more the compression caused ILDs to change dynamically over time, the greater was the overall lateral extent of the auditory event. While this relationship between $ILD_{p.p.c}$ and span seems to suggest a direct effect of compression, it should be noted that $ILD_{p.p.c}$ is influenced by the underlying characteristics of the stimulus, and these characteristics may in themselves influence how the auditory system processes the binaural cues present in the sound (e.g., Macpherson and Middlebrooks, 2002). For sounds with slow onsets, for example, envelope ITDs are less salient, and so changes in ILD caused by compression may carry a larger perceptual weight.

The exact timing of ILD changes caused by compression is also important as evidenced by a comparison of LONG IPI PT and SHORT IPI PT. The former had an IPI that was long enough (100 ms) for the compressors to release fully between pulses (nominal release time 60 ms). Consequently, at the moment of onset of every pulse within this stimulus, no ILD bias was present, although the compression was sufficiently fast-acting to introduce a bias within individual pulses. Conversely, the IPI for SHORT IPI PT (30 ms) was too short for the compressors to release fully between pulses. Thus for all

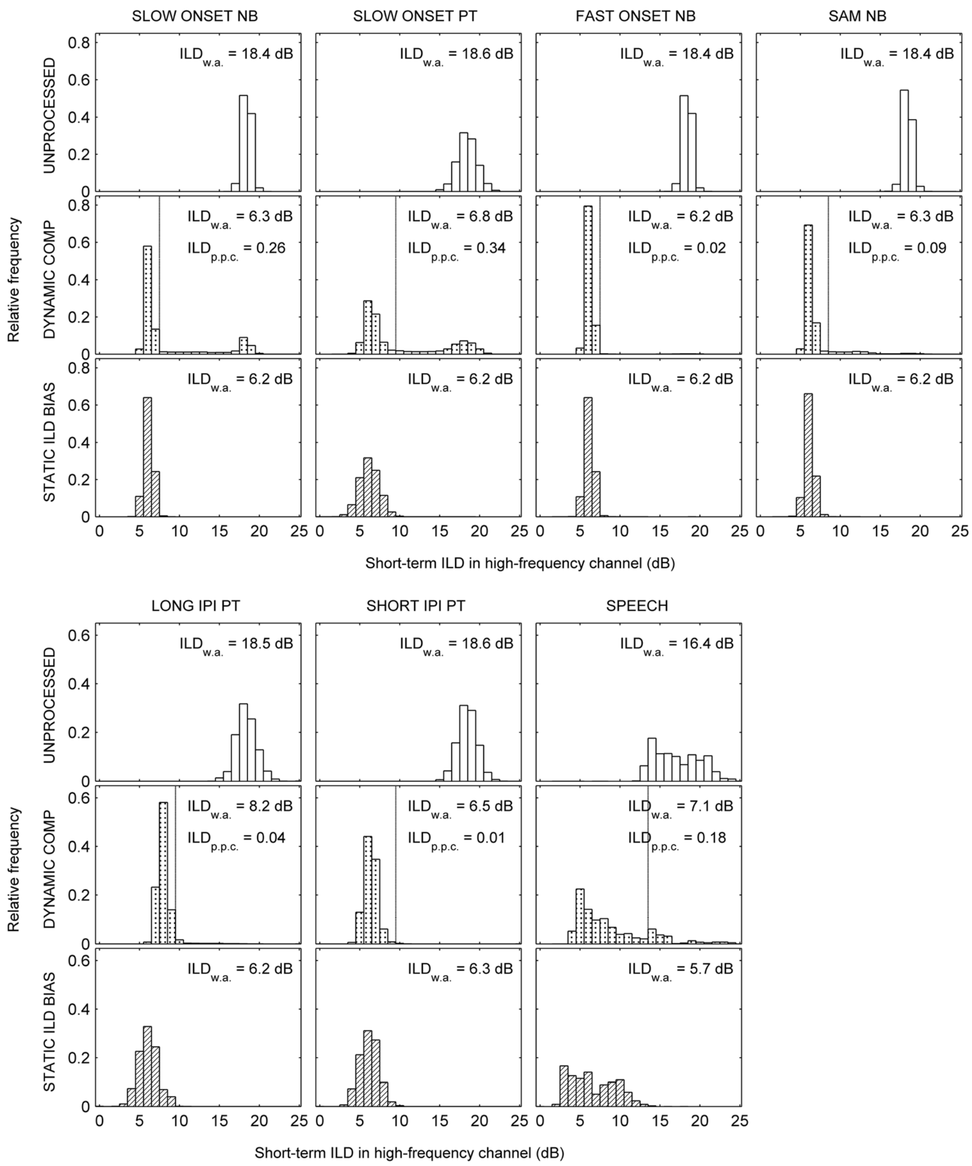

FIG. 5. Normalized histograms of the short-term interaural level difference (ILD) in the high-frequency channel. For each stimulus, three histograms are plotted, representing ILDs in the unprocessed (upper panel), dynamic compression (middle panel), and static ILD bias (lower panel) conditions. The average ILD weighted by the signal power in each analysis window is shown ($ILD_{w.a.}$). For the dynamic compression condition, the "proportion of partially compressed ILDs" ($ILD_{p.p.c.}$) is also given, equal to the proportion of ILDs exceeding the 99th percentile of all ILDs in the static ILD bias condition (indicated by the dashed vertical lines).

but the leading pulse, an ILD bias remained present at the moment of onset of each pulse. In the high-pass condition, the static ILD bias shifted the midpoint of the auditory event centrally by an average of 0.29 units for these two stimuli. For SHORT IPI PT, where only the leading pulse arrived with an uncompressed onset, the image shifted about two-thirds as far in the dynamic compression condition (0.19 units). In contrast, for LONG IPI PT, where all pulses arrived with an uncompressed onset, dynamic compression shifted the midpoint by only 0.03 units, about one-tenth as far as the static ILD bias. Musa-Shufani *et al.* (2006) suggested that listeners may be able to use brief periods of linear amplification at onsets before compression takes place, even for very short attack times: Our results for LONG IPI PT are consistent with this notion and also with previous work demonstrating lateralization dominated by binaural information present in the first few milliseconds following a stimulus onset (e.g., Houtgast and Aoki, 1994). For pulse-train stimuli, the binaural cues present in the leading pulse can often dominate the apparent position of the entire sound (Saberi and Perrott, 1995; Freyman *et al.*, 1997). However, this was not the case here because the IPI in even our SHORT IPI PT stimulus was sufficiently long to avoid dominance of the leading pulse (Stecker and Hafter, 2002).

Note that in describing the stimuli most affected by dynamic compression, the SPEECH stimulus has been grouped with the synthetic stimuli featuring gradual onsets and offsets. In reality, speech contains envelope modulations at a variety of rates, fast and slow. The apparent dominance of the slower modulations in the present study has two likely causes: (1) the envelope spectrum of running speech shows a peak at a low modulation rate of about 3 Hz (Houtgast and Steeneken, 1985); and (2) although described as "fast-acting," the time constants were such that the compressors may still have been unable to accurately track the faster modulations in the speech envelope, and thus their response would have been primarily determined by the slower modulations (Stone and Moore, 1992).

Thus far the discussion has focused on results in the high-pass condition, where the greatest effects of compression

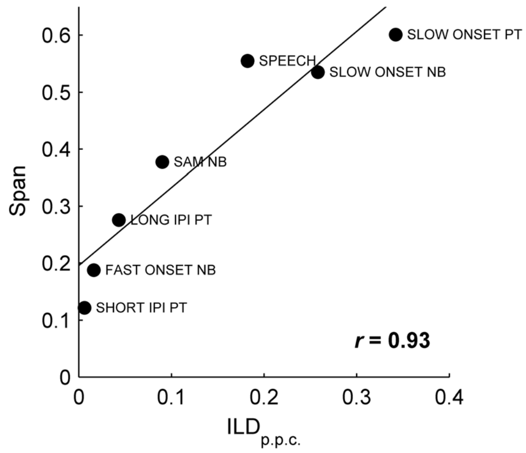

FIG. 6. Median span (average across participants) in the dynamic compression, high-pass condition plotted against the "proportion of partially compressed ILDs" ($ILD_{p.p.c.}$) for each stimulus. The positive correlation indicates that the more compression caused ILDs to change dynamically during presentation of the stimulus, the greater was the overall lateral extent of the auditory event.

were observed. In the full-bandwidth condition, there was evidence of effects in the same direction, but their magnitude was reduced. In terms of binaural cues, this can be explained as follows: (1) In the full-bandwidth condition, listeners had access to low-frequency cues, including fine-structure ITDs. Low-frequency ITDs are typically dominant for localization of wideband sounds (Wightman and Kistler, 1992; Macpherson and Middlebrooks, 2002). (2) As the processing was applied only in the high-frequency channel, low-frequency ILDs were transmitted faithfully. While ILDs are generally small at low frequencies, and therefore less useful for localization, non-negligible ILDs will have been present at frequencies toward the upper end of the low-frequency channel (ILDs were of the order of 10 dB in the 1–2 kHz region). In the full-bandwidth condition, listeners therefore had access to accurate ILDs in some auditory channels despite ILDs at higher frequencies being degraded by compression.

B. Binaural-cue weighting in conditions of dynamic versus static cue conflict

Here we consider the relative weighting of binaural cues in the high-pass condition of the experiment. As the high-frequency channel had a lower cutoff of 2 kHz, fine-structure ITDs were effectively unavailable to listeners, and so ILDs and envelope ITDs were the primary cues available for lateralizing the auditory event (Blauert, 1997).

The static ILD bias condition is comparable to previous studies in which ITDs and ILDs have been set in conflict (e.g., Wightman and Kistler, 1992; Macpherson and Middlebrooks, 2002; Seeber, 2007). These studies have shown that ILDs provide a salient cue for localization of high-pass stimuli although listeners still give some weight to envelope ITDs. Seeber (2007) reported for small cue discrepancies in a high-pass noise roughly equal weighting of ILDs and envelope ITDs. Macpherson and Middlebrooks suggested that the weight is highly variable across listeners: One listener weighted envelope ITDs roughly equally with ILDs, while the weight was lower for other listeners. In the present study, as seen in the high-pass data of Fig. 1, the static ILD bias did not shift the image as far toward the center as would be expected if ILD was the only salient cue, implying that envelope ITDs had some influence. To reach the position suggested by the reduced ILD (determined using the dummy-trial data as described in the Appendix and indicated by the dashed vertical lines in Fig. 1), the image would have had to move inwards by about 0.5 units, but the observed shift was at most 0.3 units and more typically about 0.2 units. Thus consistent with earlier studies, it seems that listeners gave roughly equal weight to ILDs and envelope ITDs at high frequencies. Note that the static ILD bias shifted the image by a reasonably similar amount for all stimuli, and so we did not observe substantial variation in the relative weighting of ILDs and envelope ITDs across the range of temporal characteristics covered by our stimuli. In contrast, Macpherson and Middlebrooks (2002) found the relative salience of envelope ITDs to increase as stimulus onset ramps were shortened and with the addition of ongoing amplitude modulation.

The dynamic compression condition represents a more unusual test situation in that time-varying conflict between ILDs and ITDs was introduced. The auditory system is sensitive to dynamic changes in binaural cues but responds to them sluggishly where object position is concerned. Dynamically changing ILDs can be followed as lateral movement if the changes occur at rates below about 5 Hz (Blauert, 1972; Grantham, 1984); faster changes can be detected but not followed in detail. The rate at which compression changed high-frequency ILDs was assessed for each stimulus. We measured the approximate duration over which the momentary ILD bias introduced by compression increased from zero to its maximal value (corresponding to a 3:1 reduction in ILD) during onset regions (averaged over multiple onsets in the case of the SPEECH stimulus). Treating this duration as if it represented the initial quarter cycle of a sinusoidal modulation of ILD, we estimated a corresponding rate in Hertz for comparison with the findings of Blauert and Grantham. For stimuli with abrupt onsets and offsets (FAST ONSET NB, LONG IPI PT, and SHORT IPI PT), compression changed ILDs at high rates ($>$ 30 Hz), well above the rates at which movement can be followed in detail. These stimuli were consistently perceived as a "single, stationary image" and the lateralization results suggest that, as for a static ILD bias, listeners gave roughly equal weight to ILDs and envelope ITDs. In contrast, for stimuli containing gradual onsets and offsets, compression changed ILDs at rates where the perception of movement may be possible (about 2 Hz for SLOW ONSET NB and SLOW ONSET PT, 7 Hz for SAM NB, and 5 Hz for SPEECH). These slower changes in ILD seem to have been followed perceptually, as listeners often reported hearing a moving/broadening or split image. In such cases, cue weighting differed: The outermost extent of the auditory event generally remained close to its position in the unprocessed condition; this position likely reflected the ILDs carried by low-level parts of the stimuli in which the compressors were inactive and by envelope ITDs at all times. In contrast, the innermost extent moved to a much more central position, approaching the position suggested by the 3:1 compressed ILD (cf. "moving/split" data in Fig. 4). This suggests that

ILDs were dominant in determining the location of the innermost extent of a moving/gradually broadening image or of the more central image in the case of a split image.

On the basis of the preceding text, we tentatively conclude that ILDs are likely to be given greater perceptual weight if they change dynamically at rates low enough to be followed in detail. It is interesting to note, however, that a few listeners seem to have been relatively insensitive to dynamically changing ILDs, responding to them as if a static ILD bias had been imposed (cf. "single, stationary" data in Fig. 4). Grantham (1984) also reported large inter-subject differences in the processing of dynamic ILDs.

C. Implications for the use of compression in bilaterally fitted hearing devices

The present study demonstrates that dynamic-range compression acting independently at each ear can affect the perceived lateral position of sounds for normal-hearing listeners, severely so in some circumstances. While it cannot be assumed that the results transfer directly to the case of hearing-impaired individuals using their clinical devices, they do suggest that the issue warrants further investigation. One factor requiring consideration is the reduction in cochlear compression that typically accompanies sensorineural hearing loss (Moore, 2007) as this may interact with the effects of compressive amplification provided externally to the ear. However, it is noteworthy that Musa-Shufani *et al*. (2006) found compressive amplification to have a similar effect on directional hearing in normal-hearing and hearing-impaired listeners. Other studies also suggest that ILD discrimination in listeners with symmetrical sensorineural hearing loss often does not differ markedly from that in normal-hearing listeners (e.g., Hawkins and Wightman, 1980; Häusler *et al*., 1983), and Simon and Aleksandrovsky (1997) found ILDs to affect the perceived lateral position of a narrow-band noise in a similar manner for hearing-impaired and normal-hearing listeners. Taken together, these studies give reason to suspect that hearing-impaired listeners may also be sensitive to changes in ILDs caused by compression in hearing devices. Nonetheless, it should be noted that individual differences in binaural-cue weighting, already present across normal-hearing listeners, may be exacerbated by differences in the details of the hearing loss across a hearing-impaired population.

The present study allows specific conditions to be identified in which unsynchronized bilateral compression is most likely to affect spatial perception. This may prove useful in guiding the design of future studies with hearing-impaired listeners, including studies that aim to evaluate the potential benefits of new algorithms that synchronize compression at the two ears. In a simple acoustic environment comprising a single sound source, the impact of compression is expected to be greatest in the following conditions:

(1) for sources away from the median plane, where naturally occurring ILDs are largest.
(2) for sounds containing predominantly high frequencies where ILDs will be more salient, or when reliable low-frequency timing cues are unavailable for some other reason.
(3) for sounds containing gradual onsets and offsets, such that there are sustained or frequent periods during which the level at one or both ears crosses the compression threshold.
(4) for higher compression ratios, which will give rise to a greater discrepancy between natural ILDs and compressed ILDs, and for faster-acting compression, which will increase the likelihood of the compressors' internal estimates of the sound level falling below the compression threshold during, for example, short pauses in speech.

To the extent that the present study allows any practical suggestions for hearing-device design to be made, the results confirm the utility of low-frequency ITDs, at least for supporting localization of wideband sounds in a simple acoustic scenario, and therefore suggest that efforts to make available and/or preserve these cues in bilateral fittings are worthwhile (e.g., Noble *et al*., 1998; Klasen *et al*., 2005). Nonetheless, the study shows that there are conditions in which compression acting independently at each ear adversely affects spatial hearing, suggesting that preservation of ILDs is also important. It remains an open question to what extent degradation of ILDs by unsynchronized compression causes deleterious effects on spatial hearing in real listening conditions, particularly in more challenging acoustic environments with multiple sources.

V. CONCLUSIONS

Normal-hearing listeners judged the lateral position of sounds spatialized using HRTFs. Two forms of processing were applied in a high-frequency channel: (1) fast-acting dynamic-range compression with a ratio of 3:1 operating independently at each ear and (2) a static ILD bias, equivalent to a 3:1 reduction in ILD. Both types of processing shifted the perceived lateral position of the auditory event toward the center of the head. A static ILD bias generally had little or no effect on the basic nature of the sound image or on its apparent diffuseness. The same was true for dynamic compression if the stimulus contained only abrupt onsets and offsets. However, for stimuli featuring gradual onsets and offsets, including speech, dynamic compression increased reports of moving and/or split images, and this was typically accompanied by a substantial increase in the overall lateral extent of the auditory event. The effects of the processing were reduced when undisturbed low-frequency information was made available to listeners.

For high-pass sounds, listeners gave on average roughly equal weight to high-frequency ILDs and envelope ITDs if the ILD bias was constant throughout the sound. When compression caused ILDs to change dynamically at rates low enough to be followed in detail, most listeners seem to have given greater weight to ILDs. A few listeners remained relatively insensitive to dynamically changing ILDs, however, and tended to respond similarly in dynamic and static conditions.

The results may have implications for the use of compression in bilateral hearing-aid and cochlear-implant fittings. Unsynchronized dynamic-range compression in such devices may have an adverse impact on spatial hearing, and the present study identifies specific conditions in which such effects are most likely to occur. The results suggest that it is likely to be beneficial to preserve both ITDs and ILDs in bilateral hearing-device fittings.

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APPENDIX: DERIVATION OF THE LATERAL POSITION SUGGESTED BY THE STEADY-STATE COMPRESSED INTERAURAL LEVEL DIFFERENCE IN THE HIGH-FREQUENCY CHANNEL

The dashed vertical lines in Fig. 1 are indicative of the position suggested by the steady-state compressed ILD in the high-frequency channel. Several steps were involved in the calculation of this position as set out in the following text.

First, the naturally occurring long-term ILD in the high-frequency channel was calculated for a test direction of $+60°$. This value was divided by three to give the steady-state "compressed ILD." The original stimulus was then filtered with HRTFs corresponding to different source azimuths, and the naturally occurring ILD in the high-frequency channel was calculated for each azimuth. The azimuth for which the naturally occurring ILD most closely matched the "compressed ILD" was determined. The resulting azimuth was consistent across the seven stimuli and was $+18°$.

The next step was to determine the average lateralization response that would be expected for a sound at a simulated azimuth of $+18°$. This was achieved with the aid of the dummy-trial results, which related to unprocessed sounds presented at azimuths between $-45°$ and $+45°$. The expected left- and rightmost extents of the auditory event for a sound presented at an azimuth of $+18°$ were determined from linear regression fits to the dummy-trial results. The implied center of the sound image was calculated as the midpoint between these extents and was found to be 0.26 units, corresponding to the position of the dashed vertical lines in Fig. 1.

A sanity check on the result of the preceding process was performed as follows: It is known that in simple lateralization experiments and for a range of different stimuli, lateral position is linearly related to ILD until the end of the response scale is reached (Blauert, 1997). In the main experiment, the center of the image for unprocessed, high-pass sounds presented at $+60°$ was on average 0.76 units. Assuming a linear relationship between lateral position and ILD, reduction of the high-frequency-channel ILD by a factor of three would be expected to shift the image center to an average position of $0.76/3 = 0.25$ units. Note that this agrees well with the position derived from the dummy-trial results.

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