Effects of Dynamic-Range Compression on the Spatial Attributes of Sounds in Normal-Hearing Listeners

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Objectives: Dynamic-range compression is routinely used in bilaterally fitted hearing devices. The objective of this study was to investigate how compression applied independently at each ear affects spatial perception in normal-hearing listeners and to relate the effects to changes in binaural cues caused by the compression for different types of sound.

Design: A semantic-differential method was used to measure the spatial attributes of sounds. Eleven normal-hearing participants responded to questions addressing certainty of location, diffuseness, movement, image splits, and externalization of sounds. Responses were given on seven-point scales between pairs of opposing terms. Stimuli included speech and a range of synthetic sounds with varying characteristics. Head-related transfer functions were used to simulate a source at an azimuth of −60° or +60°. Three processing conditions were compared: (1) an unprocessed reference condition; (2) fast-acting, wide-dynamic-range compression operating independently at each ear; and (3) imposition of a static bias in interaural level difference (ILD) equivalent to that generated by the compression under steady state conditions. All processing was applied in a high-frequency channel above 2 kHz. The three processing conditions were compared separately in two bandwidth conditions: a high-pass condition in which the high-frequency channel was presented to listeners in isolation and a full-bandwidth condition in which the high-frequency channel was recombined with the unprocessed low-frequency channel.

Results: Hierarchical cluster analysis was used to group related questions based on similarity of participants' responses. This led to the calculation of composite scores for four spatial attributes: "diffuseness," "movement," "image split," and "externalization." Compared with the unprocessed condition, fast-acting compression significantly increased diffuseness, movement, and image-split scores and significantly reduced externalization scores. The effects of compression were greater when listeners heard the high-frequency channel in isolation than when it was recombined with the unprocessed low-frequency channel. The effects were apparent only for sounds containing gradual onsets and offsets, including speech. Dynamic compression had a much more pronounced effect on the spatial attributes of sounds than imposition of a static bias in ILD.

Conclusions: Fast-acting compression at high frequencies operating independently at each ear can adversely affect the spatial attributes of sounds in normal-hearing listeners by increasing diffuseness, increasing or giving rise to a sense of movement, causing images to split, and affecting the externalization of sounds. The effects are reduced, but not eliminated, when listeners have access to undisturbed low-frequency cues. Sounds containing gradual onsets and offsets, including speech, are most affected. The effects arise primarily as a result of relatively slow changes in ILD that are generated as the sound level at one or both ears crosses the compression threshold. The results may have implications for the use of compression in bilaterally fitted hearing devices, specifically in relation to spatial perception in dynamic situations.

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INTRODUCTION

In a traditional bilateral hearing aid or cochlear implant fitting, the two devices, one worn on each ear, act independently of one another. As a result, naturally occurring differences in timing and relative level between the ears—interaural time differences (ITDs) and interaural level differences (ILDs)—may not be preserved (Van den Bogaert et al. 2006). These binaural cues play a key role in spatial hearing, and so disruption to their natural values may have deleterious effects. Dynamic-range compression, a signal-processing strategy routinely used in hearing devices, is one feature that has been recognized to distort ILDs (Byrne & Noble 1998; Moore 2008). Despite this, previous studies with both normal-hearing and hearing-impaired listeners have suggested that compression has surprisingly little effect on sound localization, that is, the objective ability to determine the direction from which a sound arrives (Keidser et al. 2006; Musa-Shufani et al. 2006). Nonetheless, the effect of compression on all aspects of spatial perception is not fully established. This study investigated the effects of compression on the perceived spatial attributes of sounds in normal-hearing listeners. The aim was to use this sensitive hearing population to identify which spatial attributes are affected by compression and to determine the stimulus conditions most likely to reveal such effects. The study should indicate whether the effect of compression on spatial perception is an issue that warrants investigation in future clinical studies and make suggestions about the types of stimuli that should be included in such studies.

Dynamic-range compression is used to compensate for the reduced dynamic range of the impaired ear (Dillon 2001). This is achieved by providing more gain to low-level sounds and less gain to high-level sounds, thereby compressing the wide range of sound levels occurring in the natural environment into a narrower range at the output of the device. When compression operates independently at the two ears, the gain provided at each ear can differ. If the sound level is greater at one ear than the other, less gain will be provided at the ear with the greater level. Compression will therefore tend to reduce any naturally occurring ILD (Byrne & Noble 1998). This reduction in the effective ILD by compression has been shown to increase ILD discrimination thresholds in normal-hearing and hearing-impaired listeners (Musa-Shufani et al. 2006) and in adults with bilateral cochlear implants (Grantham et al. 2008). In contrast, ITD discrimination thresholds are not affected by compression, because the processing alters only the level of audio signals and not their timing (Musa-Shufani et al. 2006).

As compression affects ILDs, but not ITDs, binaural cues may no longer be consistent after compression: the ILD will suggest a different source direction than the ITD. Previous studies in which normal-hearing listeners have been presented with sounds containing inconsistent cues suggest that this can have a variety of perceptual consequences. Early lateralization studies

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TABLE 2. Overview of stimuli included in the experiment

Label	Description	Spectrum	Overall Onset/Offset	Ongoing Envelope Modulation	Duration (msec)*	Level (dB SPL)†
SLOW ONSET NB	NB with gradual onset and offset	Pink noise 200 Hz–8 kHz	250 msec Gaussian rise/fall	—	1800	65
SLOW ONSET PT‡	PT with gradual onset and offset	Pink noise 200 Hz–8 kHz	250 msec Gaussian rise/fall	PT: 3 msec pulses 30 msec IPI 1 msec rise/fall	1800	65
FAST ONSET NB	NB with abrupt onset and offset	Pink noise 200 Hz–8 kHz	10 msec Gaussian rise/fall	—	1000	65
SAM NB	Sinusoidally amplitude modulated NB	Pink noise 200 Hz–8 kHz	—	SAM: 4 Hz rate 100% depth	1000	65
LONG IPI PT	PT with longer IPI	Pink noise 200 Hz–8 kHz	—	PT: 3 msec pulses 100 msec IPI 1 msec rise/fall	1000	65
SHORT IPI PT	PT with shorter IPI	Pink noise 200 Hz–8 kHz	—	PT: 3 msec pulses 30 msec IPI 1 msec rise/fall	1000	65
SPEECH	"They moved the furniture." Male talker.	—	—	—	1400	65

*Total duration including any overall onset and offset time.

†Steady state level of noise before envelope application; root-mean-square level for the sentence. Levels correspond to the free-field sound pressure level at the center of a simulated head.

‡Note that SLOW ONSET PT and SHORT IPI PT shared identical pulse-train parameters, the only difference between the two stimuli being the overall slow onset and offset applied to SLOW ONSET PT and its correspondingly longer overall duration.

IPI, interpulse interval; NB, noise burst; PT, pulse train; SAM, sinusoidal amplitude modulation.

sentence from the Institute of Hearing Research Sentence List was used throughout (Macleod & Summerfield 1990).

The stimuli described in Table 2 were not presented to participants directly: rather, they formed the input to the signal processing stages described in the following section.

Signal Processing

The virtual-auditory-space method was used to simulate a source in the frontal horizontal plane at an azimuth of −60° or +60°. Each of the seven stimuli was filtered with HRTFs to introduce realistic binaural cues for the location in question. The same HRTF set was used for all participants, so that naturally occurring (simulated) ILDs, and therefore also the effect of compression on ILDs, would not vary between participants. A single HRTF set from the AUDIS catalog was used ("moe," Blauert et al. 1998). In a previous study, this was found to be the HRTF set selected most often following a procedure designed to improve performance with respect to localization error, variance, front–back confusions, and externalization of sounds (Seeber & Fastl 2003). The HRTF set used had been equalized for use with diffuse-field-equalized headphones, and the headphones used in this study were also diffuse-field equalized. We did not attempt to compensate for individual differences in the headphone transfer function between subjects.

A block diagram of the processing scheme is shown in Figure 1. At each ear, the signal was split into a low- and a high-frequency channel with a crossover frequency of 2 kHz. Linear-phase finite impulse response filters (256 taps) were used to avoid phase distortion. The stop-band attenuation of the filters was more than 55 dB, and the two channels had a flat magnitude response when combined. The pure delay introduced by the filters was compensated for. The sampling frequency was 44.1 kHz.

As indicated in Figure 1, compression was applied only in the high-frequency channel. Several factors guided this decision. This configuration reflects, in a simplified manner, 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 (Dillon 2001). The greatest effects of compression on spatial hearing were also anticipated with the compressors operating in a high-frequency channel, as naturally occurring ILDs are larger at high frequencies. Last, by leaving the low-frequency channel unprocessed, it was possible to assess the benefit of undisturbed low-frequency binaural cues to normal-hearing listeners. In theory, the use of open-fitting hearing aids may allow some hearing-impaired individuals access to undistorted low-frequency cues (Noble et al. 1998).

Three different high-frequency-channel processing conditions were included in the experiment.

Unprocessed Condition • This condition was included as a control. Signals passed through the high-frequency channel unaltered, and so listeners were presented with undisturbed binaural cues.

Dynamic Compression Condition • Dynamic-range compression, representative of the type of processing that might occur in a generic hearing device, was applied independently at each ear. The compressors provided linear amplification below the compression threshold, and compressive amplification with a constant ratio above threshold. The signal level was estimated using a peak-detector algorithm (Kates 2008). The peak detector used different attack and release time constants so as to respond quickly to increases in the signal level but to track decreases in the signal level more slowly. The parameters of the compressors were set to provide fast-acting, wide-dynamic-range compression: ratio 3:1, threshold 30 dB SPL within the high-frequency channel, attack time 5 msec, and release time 60 msec.

TABLE 3. Statistical test results for overall effects of processing condition

	Friedman's ANOVA	Dynamic Compression vs. Unprocessed	Static ILD Bias vs. Unprocessed
Diffuseness			
High pass	**$\chi^2(2) = 26.66$, $p < 0.001$**	**3.8 vs. 2.8 (+1.0), $p < 0.001$**	3.0 vs. 2.8 (+0.3), $p = 0.103$
Full bandwidth	**$\chi^2(2) = 6.51$, $p = 0.039$**	3.8 vs. 2.8 (+1.0), $p = 0.044$	3.0 vs. 2.8 (+0.3), $p = 0.328$
Movement			
High pass	**$\chi^2(2) = 54.71$, $p < 0.001$**	**4.2 vs. 2.5 (+1.7), $p < 0.001$**	2.8 vs. 2.5 (+0.3), $p = 0.068$
Full bandwidth	**$\chi^2(2) = 15.79$, $p < 0.001$**	**2.5 vs. 2.3 (+0.2), $p = 0.001$**	2.3 vs. 2.3 (−0.0), $p = 0.526$
Image split			
High pass	**$\chi^2(2) = 39.46$, $p < 0.001$**	**4.0 vs. 2.5 (+1.5), $p < 0.001$**	**3.0 vs. 2.5 (+0.5), $p = 0.003$**
Full bandwidth	**$\chi^2(2) = 18.02$, $p < 0.001$**	**3.5 vs. 2.8 (+0.8), $p = 0.005$**	2.5 vs. 2.8 (−0.3), $p = 0.609$
Externalization			
High pass	**$\chi^2(2) = 17.45$, $p < 0.001$**	**4.0 vs. 5.0 (−1.0), $p = 0.003$**	**4.0 vs. 5.0 (−1.0), $p < 0.001$**
Full bandwidth	$\chi^2(2) = 2.04$, $p = 0.360$	—	—

The Friedman's ANOVA column gives the result of the omnibus test comparing all three processing conditions. The rightmost two columns give the median scores for the specific processing conditions being compared in any follow-up tests (plus the difference between the medians), and the unadjusted p *value for the sign test. Significant test results (after Bonferroni correction in the case of follow-up tests) are shown in bold.*

ANOVA, analysis of variance; ILD, interaural level difference.

between processing conditions, ranged from 0.3 to 4.5 units on the seven-point scale.

Figure 4 confirms the tendency toward increased diffuseness, movement and image-split scores, and reduced externalization scores in the dynamic compression condition. However, it is clear that some stimuli were affected more than others. As can be seen from Table 4, for SLOW ONSET noise burst (NB), SLOW ONSET pulse train (PT), sinusoidal amplitude modulation (SAM) NB, and SPEECH, scores on one or more of the diffuseness, movement, or image-split attributes were significantly greater in the dynamic compression condition than in the unprocessed condition. In the high-pass condition, the difference in median scores was between 0.7 and 4.5 scale units. The difference was smaller in the full-bandwidth condition (0.3–1.8 scale units), although the effect remained statistically significant in four out of nine cases. For the other three stimuli, FAST ONSET NB, LONG interpulse interval (IPI) PT, and SHORT IPI PT, there were no significant differences between the dynamic compression and unprocessed conditions on any spatial attribute. Despite a general tendency for lower externalization scores in the dynamic compression condition, the effect was not statistically significant for any individual stimulus.

In contrast to the effects of dynamic compression, differences between the static ILD bias and unprocessed conditions were generally small. Table 4 shows that the effect of the static ILD bias was statistically significant in only two cases, both in the high-pass condition: image-split scores for FAST ONSET NB (difference in median of 1.0 scale units) and externalization scores for SHORT IPI PT (difference in median of 1.5 scale units).

DISCUSSION

Compression Adversely Affects Spatial Perception

Normal-hearing listeners consistently rated sounds more highly for diffuseness, movement, and image splits after compression at high frequencies. These can be considered deleterious effects on spatial perception. Increases in diffuseness, movement, and image-split scores tended to co-occur. This can be explained by considering the effect of compression on binaural cues. Compression primarily affects ILDs, leaving ITDs essentially undisturbed, and so introduces inconsistency between the two types of cue. It is shown below that, for the stimuli most affected by the processing, compression generates dynamic changes in ILD at relatively low rates of change. Previous studies have shown that movement of the sound image is perceived if ILDs change slowly over time (Blauert 1972; Grantham 1984). However, in the real world, a physically moving sound source would give rise to consistent changes in both ILD and ITD. In this study, because only ILDs were changed by the compression, the percept was typically, in the experience of the authors, of a component of movement within the sound, rather than of a clearly defined moving object. Thus, an apparent broadening of the sound image, or increased sense of diffuseness, tended to accompany the perception of movement. Furthermore, if the ILD-shifted image moved sufficiently far from its original location (as represented throughout by the unaffected ITDs), there was a tendency for the sound to split into two images. As each question was asked on a separate trial, participants could report increased diffuseness, movement, and occurrence of image splits for the same sound: they were not forced to select which of these effects was the dominant percept.

There was an overall tendency for sounds to be less well externalized after compression. Hartmann and Wittenberg (1996) showed that setting ILDs to zero, while retaining interaural phase differences, reduces externalization, and that ILDs in all frequency ranges are of similar importance in this respect. In this study, compression reduced high-frequency ILDs toward (but not to) zero, while leaving low-frequency ILDs unaffected. It is likely that this reduction in high-frequency ILDs, and the resulting conflict introduced between ITDs and ILDs, was responsible for the decrease in externalization scores. The effect was rather small, however, and, across all stimuli, statistically significant only in the high-pass condition. It is possible that a clearer effect may have been revealed had individualized HRTFs been used.

Some Sounds Are More Susceptible to the Effects of Compression Than Others

Compression consistently affected the spatial attributes of some stimuli but not others. The spectral and temporal

TABLE 4. Significant effects of the processing on the spatial attributes of individual stimuli

	Dynamic Compression vs. Unprocessed		Static ILD Bias vs. Unprocessed	
	High pass	Full bandwidth	High pass	Full bandwidth
SLOW ONSET NB				
Diffuseness	5.3 vs. 4.3 (+1.0), $p = 0.005$	—	—	—
Movement	5.7 vs. 4.2 (+1.5), $p = 0.014$	4.7 vs. 3.2 (+1.5), $p = 0.003$	—	—
Image split	4.5 vs. 2.0 (+2.5), $p < 0.001$	4.8 vs. 3.0 (+1.8), $p = 0.004$	—	—
SLOW ONSET PT				
Movement	6.0 vs. 5.3 (+0.7), $p = 0.022$	5.8 vs. 5.5 (+0.3), $p = 0.013$	—	—
FAST ONSET NB				
Image split	—	—	2.3 vs. 1.3 (+1.0), $p = 0.008$	—
SAM NB				
Diffuseness	3.8 vs. 1.8 (+2.0), $p < 0.001$	—	—	—
Movement	2.5 vs. 1.8 (+0.7), $p = 0.008$	—	—	—
LONG IPI PT	—	—	—	—
SHORT IPI PT				
Externalization	—	—	4.0 vs. 5.5 (−1.5), $p = 0.008$	—
SPEECH				
Diffuseness	5.3 vs. 3.0 (+2.3), $p = 0.007$	—	—	—
Movement	6.5 vs. 2.0 (+4.5), $p = 0.002$	1.8 vs. 1.2 (+0.7), $p = 0.016$	—	—
Image split	5.3 vs. 2.8 (+2.5), $p = 0.002$	—	—	—

Median scores for the two conditions being compared in each case are given (plus the difference between these). The stated p values are the unadjusted results of the Wilcoxon signed-rank tests, which were performed only when the preceding Friedman test indicated a significant overall effect of processing condition. All individual effects reported here were significant at the 0.05 level after Bonferroni correction.

ILD, interaural level difference; IPI, interpulse interval; NB, noise burst; PT, pulse train; SAM, sinusoidal amplitude modulation.

characteristics making certain stimuli more susceptible to the effects of compression are discussed below.

Spectral Characteristics • The effects of compression were invariably greater in the high-pass condition than in the full-bandwidth condition. Given that compression was applied only in the high-frequency channel, it is not surprising that listeners were more sensitive to the processing when listening to this channel in isolation. In the full-bandwidth condition, listeners additionally had access to undisturbed low-frequency cues, which seemingly reduced the perceptual influence of the distorted high-frequency cues. In part, this likely reflects the dominance of ITDs as cues for sound localization for wideband stimuli containing low frequencies (Wightman & Kistler 1992). In addition, listeners would have had access to nonnegligible undisturbed ILDs at frequencies around 1 to 2 kHz in the full-bandwidth condition, which may have helped to counter the effect of altered ILDs above 2 kHz. In general, compression can be expected to have a greater effect on spatial perception for sounds containing relatively more energy at high frequencies. Nonetheless, for natural wideband sounds with more energy at low frequencies than high, such as the SPEECH stimulus of the present experiment, compression applied at high frequencies still had a measurable, albeit relatively small, effect on spatial perception.

Temporal Characteristics • The stimuli that consistently revealed significant effects of compression were SLOW ONSET NB, SLOW ONSET PT, SAM NB, and SPEECH. These stimuli all contained gradual onsets and offsets, either in the form of an overall slow onset and offset (SLOW ONSET NB and SLOW ONSET PT) or as a result of ongoing envelope modulations (SAM NB and SPEECH). In the real world, a gradual onset or offset to a sound may arise from an approaching or receding object, while signals such as speech naturally contain envelope modulations at a variety of rates. Stimuli that contained relatively abrupt onsets and offsets (FAST ONSET NB, LONG IPI PT, and SHORT IPI PT) showed no significant effects of compression. It is concluded that sounds containing gradual onsets and offsets are more susceptible to the effects of compression on spatial attributes.

This was investigated further by analyzing the effect of compression on ILDs. Figure 5 shows the effect of the processing on high-frequency-channel ILDs for a stimulus that did not reveal any significant effects of compression (FAST ONSET NB) and for two stimuli for which compression increased diffuseness, movement, and image-split scores (SLOW ONSET NB and SPEECH). Unprocessed ILDs are seen to be about 18 dB on average, with some fluctuation about this value. The fluctuation is greater for SPEECH than for the two noise-based stimuli because of the greater variation in the short-term spectral content of speech. As intended, the static ILD bias reduced all ILDs by a factor of three. The magnitude of the ILD bias imposed in the high-frequency channel was therefore approximately 12 dB, which is comparable to the size of the bias introduced in previous conflicting-cue studies (e.g., Gaik 1993; Macpherson & Middlebrooks 2002).

After dynamic compression, ILDs are seen to vary in magnitude between those in the unprocessed and static ILD bias conditions, most notably for SPEECH. The size of the reduction in ILD at any instant is related to whether the level at neither, one, or both of the ears is above the compression threshold. When the level at neither ear is above threshold, linear amplification is provided and natural ILDs are preserved. When the level at both ears is above threshold, a steady state is reached in which ILDs are reduced by a factor of three, corresponding to the 3:1 compression ratio. However, when the level at only one of the ears is above threshold, compression reduces the ILD by an intermediate amount. For FAST ONSET NB, the level at both ears increases above the compression threshold almost immediately

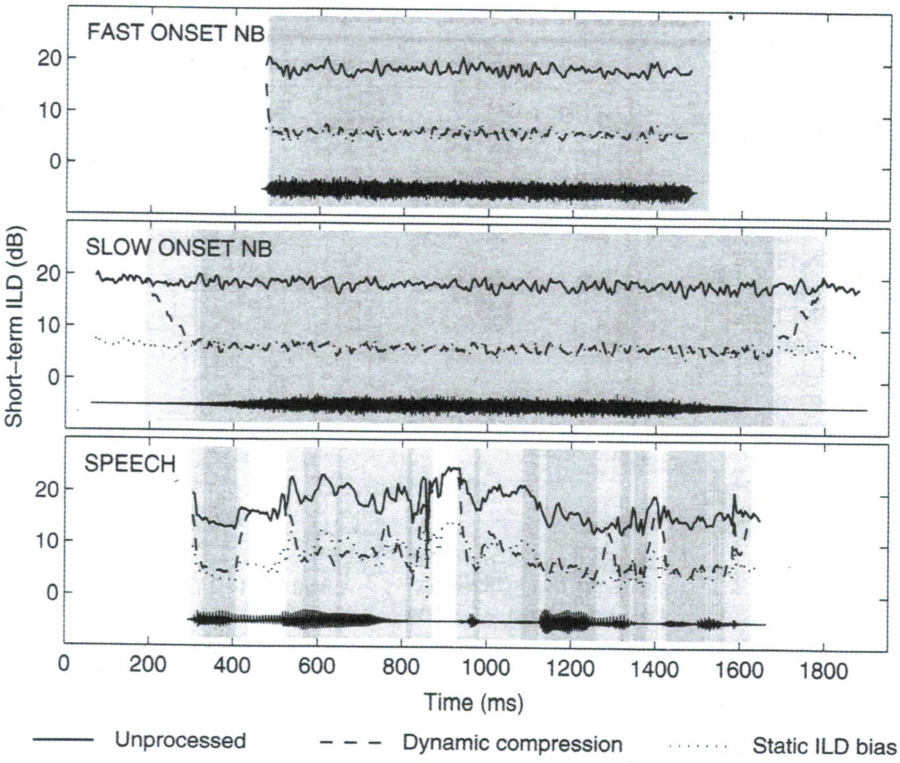

Fig. 5. Effects of high-frequency-channel processing on short-term interaural level differences (ILDs) for the FAST ONSET noise burst (NB) (upper panel), SLOW ONSET NB (middle panel), and SPEECH (lower panel) stimuli presented from +60°. ILDs were calculated in 10 msec rectangular windows with 50% overlap. Shading indicates periods in which the level at neither (white background), only one (lighter gray background), or both (darker gray background) ears was above the compression threshold. The waveforms of the original wideband stimuli are plotted below the ILD traces for reference.

after the fairly abrupt onset of the sound, and hence the ILD trace rapidly approaches the steady state compressed value. In contrast, for SLOW ONSET NB, there are periods of about 100 msec during the onset and offset of the sound in which the level at only one of the ears is above the compression threshold. During these periods, ILDs change gradually between the original and steady state compressed values. For SPEECH, the situation is more complicated, but it can be seen that ILDs after compression fluctuate between the original and steady state compressed values as the level at one or both ears crosses the compression threshold. The results of the experiment indicate that it is these slowly varying dynamic changes in ILDs, generated only for sounds containing gradual onsets and offsets, which are principally responsible for the increased diffuseness, movement, and image-split scores after compression.

Further evidence for the importance of the dynamic nature of the changes to ILDs introduced by compression comes from the fact that, for the same peak conflict between ITDs and ILDs, dynamic compression had a substantially greater perceptual effect than a static ILD bias. For instance, when considering the effect of the processing on the spatial attributes of individual stimuli, dynamic compression had a statistically significant effect in a total of 13 cases, whereas the effect of a static ILD bias was significant in only two cases (Table 4). Thus, it seems that conflict between binaural cues per se is not critical, but rather that the changes in spatial perception depend on the way that compression dynamically alters ILDs.

The LONG IPI PT and SHORT IPI PT pulse-train stimuli were included to test the effect of the timing of pulses relative to the compressor time constants. The LONG IPI PT stimulus comprised short pulses separated by 100 msec gaps. The nominal release time of the compressors was 60 msec, and thus the gaps were long enough for the compressors to release fully between pulses. In contrast, the gaps between pulses for SHORT IPI PT were 30 msec, and so there was insufficient time for the compressors to fully release between pulses. For this reason, it was expected that compression would have a greater effect on SHORT IPI PT than on LONG IPI PT. In fact, compression did not have any significant effect on the spatial attributes of either stimulus. This is attributed to the fact that neither stimulus contained gradual onsets or offsets, and consequently compression did not generate any slowly varying ILDs. It is, however, possible that compression may have affected the perceived lateral position of these stimuli: the method used in this study was not sensitive to static position shifts.

An interesting comparison can be made between the SLOW ONSET NB and SLOW ONSET PT stimuli. Both had the same overall slow onset and offset, and so dynamic compression caused ILDs to change gradually at the beginning and end of the sound (as depicted for SLOW ONSET NB in Fig. 5). For both stimuli, compression significantly increased movement scores in both the high-pass and full-bandwidth conditions, demonstrating that the gradually changing ILDs were followed perceptually. Compression also had a clear effect on image-split scores for SLOW ONSET NB in both bandwidth conditions but had no significant effect on image-split scores for SLOW ONSET PT. It is suggested that repeated onsets in the pulse-train stimulus (SLOW ONSET PT), which were not present in SLOW ONSET NB, may have acted as a grouping cue (Cooke & Ellis 2001), helping to keep the sound fused into a single image, even though this image appeared to move.

Potential Implications for the Use of Compression in Bilaterally Fitted Hearing Devices

This study demonstrates that dynamic-range compression acting independently at each ear has deleterious effects on spatial perception for normal-hearing listeners. It is possible that the use of unsynchronized compression in bilaterally fitted hearing devices has similar effects. There are, however, potentially important differences between our normal-hearing listeners and the typical users of compressive hearing devices. For instance, a primary rationale for using compression is to compensate for reduced or absent cochlear compression in the impaired ear. The resulting loudness recruitment may mean that ILD perception differs in hearing-impaired listeners compared with normal-hearing listeners (Moore 2007). Nonetheless, it has been found that ILD discrimination in listeners with symmetrical sensorineural hearing loss often does not differ markedly from that in normal-hearing listeners (e.g., Hawkins & Wightman 1980; Häusler et al. 1983), and Musa-Shufani et al. (2006) found compression to have a similar effect on directional hearing for normal-hearing and hearing-impaired listeners. Furthermore, this study highlights the importance of the dynamic nature of compression, and, as has been noted elsewhere, the time constants used in compressive hearing devices are such that the processing cannot directly compensate for the dynamic aspects of loudness recruitment (Stone et al. 2008). Further study is therefore needed to test whether compression affects spatial perception in clinical populations using compressive hearing devices.

One should also note that the normal-hearing listeners of this study took part in a familiarization session before data collection began. The purpose of this session was to make listeners consciously aware of the types of image degradation that can occur when conflicting and dynamically changing binaural cues are present and to encourage them to listen analytically to the spatial attributes of sounds. In real-life situations, and in the absence of such familiarization, it is possible that listeners would not be consciously aware of the types of effects reported here. However, that is not to say that the distortion of binaural cues underlying these effects might not still restrict access to the full benefits normally conferred by binaural listening, especially in dynamic situations (Gatehouse & Akeroyd 2006).

The adverse effects observed in this study result from the independent action of the compressor at each ear. It has been proposed that synchronizing the compression at the two ears by means of a wireless communications link, thereby preserving natural ILDs, may improve sound quality, localization, and speech understanding for hearing aid users (Sockalingam et al. 2009; Kreisman et al. 2010). Although past studies suggest that synchronizing compression across the ears is perhaps not crucial for accurate sound localization (Keidser et al. 2006; Musa-Shufani et al. 2006), the methods used in this study may provide a useful means of evaluating such processing strategies in relation to other aspects of spatial perception.

CONCLUSIONS

Normal-hearing listeners rated the spatial attributes of sounds processed by a simulation of fast-acting dynamic-range compression operating independently at each ear. The results show that compression applied in a high-frequency channel can make the sound image more diffuse, increase or create the perception of movement, lead to image splits (the percept that the sound arrived from more than one direction at once), and result in less well externalized sounds.

The effects are primarily related to dynamic changes in ILDs introduced by compression, and the resulting conflict between binaural cues. The sounds most likely to be affected are those that contain gradual onsets and offsets, including speech. The effects of compression are generally reduced when listeners have access to undisturbed low-frequency information, although remain pronounced for some full-bandwidth sounds.

The adverse effects mostly result from the independent action of the compressor at each ear. Further study is needed to establish whether the use of unsynchronized compression in bilaterally fitted hearing devices has a similar effect on the spatial perception of sounds.

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