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Research Paper

A loudness model for time-varying sounds predicts asymmetries in estimates of loudness change for sounds that increase or decrease in level

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ABSTRACT

Previous research has demonstrated a robust asymmetry in loudness judgements for rising and falling level tone stimuli, showing greater loudness and loudness change for rising sounds. In the literature, this has been interpreted to reflect an adaptive perceptual bias, resulting from an evolutionary advantage that increases the margin of safety when reacting to an approaching sound-producing object. The current experiment tested whether a loudness model was able to predict asymmetries in loudness-change judgments for rising and falling sounds, providing an alternative explanation to the adaptive perceptual bias theory. Blindfolded participants were presented with 1-kHz tones that increased or decreased in level by 15 dB, with different ranges of presentation levels (60/75, 65/80, 70/85, 75/90 dB). They were asked to report how much each sound changed in loudness, either verbally or using a tactile slider. Participants reported greater loudness changes for rising than falling tones for both response modes, the asymmetry increasing with increasing overall level. The results were accurately predicted by a loudness model, suggesting that an adaptive perceptual bias is not necessary to explain asymmetry in loudness-change estimates for rising and falling level sounds.

1. Introduction

It has been posited that evolution has resulted in a beneficial perceptual bias for approaching sound sources, especially for tonal stimuli. This has been referred to as the adaptive looming bias theory (Neuhoff, 2016) or adaptive perceptual bias theory (McCarthy et al., 2017). Consistent with this, rising level sounds are often judged to change in loudness by a greater amount than equivalent falling level sounds (Neuhoff, 1998, 2001). Approaching sounds have been reported to be judged as starting and stopping closer to the listener than equivalent receding sounds (Kolarik et al., 2026; Neuhoff, 2001). A related bias has been demonstrated for rhesus monkeys, who orient to rising-level tones for significantly longer than to falling-level tones (Ghazanfar et al., 2002). Loudness is the perceptual correlate of level, a primary cue to the distance of sound sources (Cochran et al., 1968; Kolarik et al., 2013; Simpson et al., 1973) that also provides information regarding whether the sound is approaching (rising level) or receding (falling level). According to the perceptual bias theory, a bias for rising-level sounds provides a selective advantage as rising level can indicate movement of the sound source towards an organism (Neuhoff, 1998). It has been argued that looming sounds are likely prioritized in perceptual processing because of the potential threat of approaching objects (McCracken et al., 2021), and the bias increases the margin of safety in response to an approaching potential danger (Ghazanfar et al., 2002). However, it is unclear whether perceptual bias theory is the model that explains the asymmetry in judgments of loudness change between rising- and falling-level sounds, especially if the sound is not considered to be threatening, as the asymmetry may be predicted by a loudness model for time-varying sounds (ISO 532-3, 2022; Moore et al., 2018). This is investigated in the current study.

Kolarik et al. (2026) presented participants with virtual anechoic approaching, receding, and static tones and white noise. Dynamic

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stimuli were simulated to move 11 m across close, middle and far distance ranges. Participants reported the judged start and end distances of the sounds. The pattern of results was in line with two predictions of the adaptive perceptual bias theory: (1) that estimates of the start and end distances of approaching sounds would be smaller than for receding sounds that travelled over equivalent distances; and (2) that asymmetries would be larger for closer than for farther distances. However, the results were not consistent with two other predictions, that (1) asymmetries would be greater for tones than noise, because tones are more reliable markers for individual sound sources compared to noise (Ghazanfar et al., 2002); and (2) approaching sounds would be estimated to move over a larger distance than equivalent receding sounds. The data agreed with the predictions of a loudness model for time-varying sounds (ISO 532-3, 2022; Moore et al., 2018), suggesting that distance judgments for static and dynamic sounds are based on loudness, in environments where level is the primary distance cue available.

Although the findings of Kolarik et al. (2026) show that the loudness model can predict asymmetry for virtual distance judgments, more evidence is needed to establish whether the loudness model is able to explain reported asymmetries in loudness-change judgments for rising- and falling-level sounds (Neuhoff, 1998, 2001). Previous work (Ponsot et al., 2015b) tested whether an earlier version of the loudness model (Glasberg et al., 2002) could explain such asymmetries, in a study where participants gave a number proportional to the global loudness of each sound after listening to rising and falling-level stimuli. It was reported that although asymmetries in the correct direction were predicted, they were too small to account for the experimental findings. In more recent updates to the loudness model (Moore, 2014), the time constants were changed, resulting in greater predicted asymmetry. The current study tested whether the current version of the loudness model was able to predict asymmetries in loudness-change judgments for rising and falling sounds, thus providing an alternative explanation to adaptive perceptual bias theory.

The current study design was similar to that of Neuhoff (1998), in which participants judged the loudness change of rising and falling level stimuli across different level ranges; participants responded using a visual analog scale. To assess whether results similar to those of Neuhoff (1998) would be obtained using response modes not involving vision, in the current study two non-visual response modes were used (verbal and via a tactile slider). Tones were used as stimuli, since they have been reported to show a large asymmetry between rising and falling level sounds (Neuhoff, 1998; Ponsot et al., 2015a, 2015b).

Based on previous findings (Neuhoff, 1998; Ponsot et al., 2015a, 2015b), it was hypothesized that, for both response modes, judged level changes would be greater for rising- than for equivalent falling-level sounds, with larger asymmetry for higher overall levels. The effectiveness of a loudness model for predicting asymmetry in loudness judgments for rising and falling level tones was explored.

2. Materials and methods

2.1. Participants

There were 10 participants, 6 female and 4 male, with a mean age of 35 years, range 21–49 years. The number of participants tested was similar to that for a previous experiment involving rising and falling level sounds on which the current experimental design was based (Neuhoff, 1998, n = 12). All participants had normal or near-normal hearing, defined as pure-tone average (PTA) better-ear hearing thresholds averaged across 0.5, 1, 2, 4, and 8 kHz less than or equal to 25 dB HL. Hearing was assessed using audiograms obtained using the procedures of the British Society of Audiology (2011). All participants provided written informed consent. The experiments followed the tenets of the Declaration of Helsinki, and ethical approval was provided by the ethics panel of Anglia Ruskin University on 5th August 2021 (application number FST/FREP/13/403).

2.2. Apparatus and stimuli

The stimuli were 1-kHz sinusoidal tones with a duration of 2 s, with 100-ms rise/fall linear ramps. Tones rose or fell in level by 15 dB, over the following ranges: 60/75, 65/80, 70/85, 75/90 dB SPL. The stimuli were chosen to be similar to those used in previous experiments that assessed loudness judgments for tone stimuli (Neuhoff, 1998; Ponsot et al., 2015b). The stimuli were presented diotically, as in Ponsot et al. (2015b). Reponses were made either verbally or using a hand-held tactile slider consisting of a moveable marker that ran along a 7-cm long groove, held in the participant's preferred hand, quantised (based on MIDI signals limited to 7 bits, representing 128 discrete values, 0 to 127), divided by 127, and rounded giving values between 0 and 100, in proportion to the position of the moveable marker. The experiment took place in a quiet 7.5 × 8 × 3 m experimental room with painted walls, standard office mineral fibre ceiling tiles, and carpeted floor. Tables and equipment were positioned against the walls, and participants were seated in a secluded, low-noise, low-distraction listening space. Sounds were presented using an ESI MAYA22 sound card (Leonberg, Germany) and Sennheiser HD650 headphones (Sennheiser Electronics, Wedemark, Germany) at a sampling frequency of 44.1 kHz, using custom-written MATLAB (Mathworks, Natick, MA) script.

2.3. Procedure

Participants were instructed that they would hear sounds that would increase or decrease in loudness and have different overall loudness values. They were asked to report how much each sound changed in loudness, i.e. how much the loudness at the start differed from the loudness at the end of the sound, and to report this using either a verbal or tactile scale. For tactile responses, participants were instructed that the marker scale of the slider represented "no change" when placed at the bottom of the groove, and "large change" at the top. These parameters were also used by Neuhoff (1998) in an experiment that used a visual analog response scale. Before each stimulus was played, participants were asked to move the marker of the slider to the bottom of the scale. The adjusted slider position was recorded on the computer. In the verbal report condition, the change in loudness was reported on a scale ranging from 0 (no change) to 100 (large change) and recorded by the experimenter. No familiarisation or feedback was provided, as was the case for the study of Neuhoff (1998).

After receiving instructions, participants were blindfolded and started the experiment. After each stimulus was presented, the participant was given 5 s to respond. Stimuli were presented in two blocks of 80 trials for each of the two response modes (4 level ranges × 2 directions (rise/fall) × 10 repetitions for each stimulus) for a total of 160 trials. The stimuli were presented in a randomized order within each block, and the order of response-mode use was counterbalanced. Overall, the experiment took approximately 30 min per participant.

3. Results

Fig. 1 shows mean judged loudness change for rising and falling tones. Rising level tones were judged to change more than falling level tones in all conditions, with loudness change judged to be larger for higher level ranges. The pattern of results was similar for the verbal (panel A) and tactile (panel B) response conditions, and both were similar to data collected by Neuhoff (1998), which are shown in panel C. Loudness-change judgments are freely available at the OSF repository [https://osf.io/kwcm4/overview?view_only=6c60ecb3dbe8476 9883fe82f155f0ce6].

Loudness-change ratings were analysed using repeated-measures analysis of variance (ANOVA) with level range (60/75, 65/80, 70/85, 75/90 dB), direction (rising or falling) and response mode (verbal or

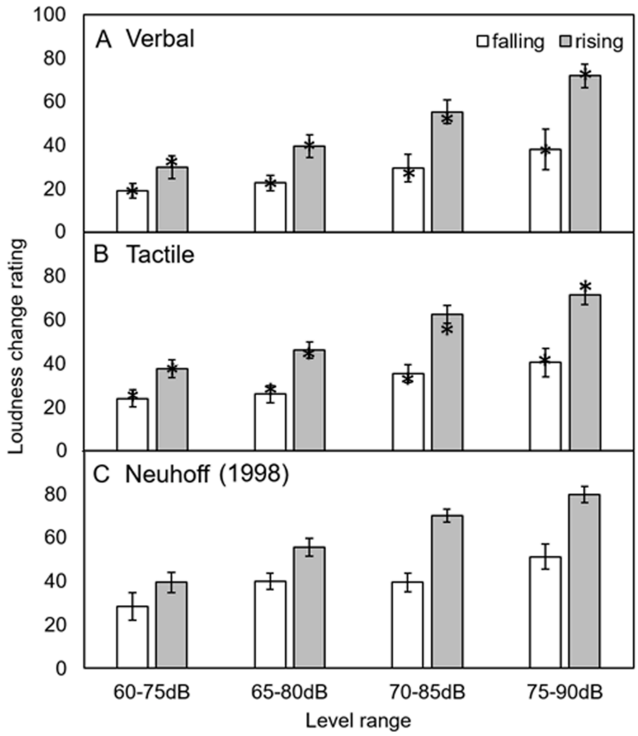

Fig. 1. Mean judged loudness change for rising and falling tones. Panel A shows data for the verbal response mode, panel B for the tactile response mode, and panel C data replotted from Neuhoff (1998) based on visual analog scale units, from their Table 2 (labelled as "sinusoid" values). Error bars show ±1 standard error across participants. Asterisk symbols in panels A and B indicate predictions using the loudness model (described later).

tactile) as within-subjects factors. The Greenhouse-Geisser procedure was used to correct the degrees of freedom where sphericity was violated. There were main effects of level range [$F(1.20, 10.81) = 30.35$, $p < 0.001$, $\eta_p^2 = 0.77$] and direction [$F(1, 9) = 24.83$, $p < 0.001$, $\eta_p^2 = 0.73$], and a significant interaction between level range and direction [$F(1.40, 12.60) = 15.52$, $p < 0.001$, $\eta_p^2 = 0.63$]. There were no other significant main effects or interactions ($p > 0.05$). Post-hoc tests with Bonferroni correction indicated significantly larger loudness-change ratings for rising than for falling sounds for all conditions, except for the lowest level range (60/75 dB).

4. Predictions using the loudness model

Predictions of loudness, in sones, were generated using the loudness model of Moore et al. (2018), as implemented in ISO 532-3 (2022). Among other things, the model gives a running estimate of the momentary impression of loudness, called short-term (ST) loudness. The ST loudness is estimated every 1 ms as a running average of the estimated instantaneous loudness. The instantaneous loudness is assumed not to be available for conscious perception, although it may be represented in the brain (Glasberg et al., 2002; Thwaites et al., 2016). The estimation of ST loudness in each frequency channel resembles the operation of an automatic gain control circuit, with an attack time, *Ta*, and a release time, *Tr*. S'*n* is defined as the running ST loudness estimate at the time corresponding to the *n*th frame, S*n* as the instantaneous specific loudness at the *n*th frame, and S'*n-1* as the ST loudness at the time corresponding to frame *n-1*.

If S*n* > S'*n-1* (corresponding to an attack, or increase in level, as the instantaneous loudness at frame *n* is greater than the ST loudness at the previous frame), then

$$S'_n = a_a S_n + (1 - a_a) S'_{n-1}, \quad (1)$$

where *αa* is a constant that is related to *Ta* according to:

$$a_a = 1 - exp(-T_0 / T_a) \quad (2)$$

where T_0 is the time interval (1 ms) between successive values of the instantaneous loudness.

If S*n* ≤S'*n-1* (corresponding to a release, or decrease in level, as the instantaneous loudness at frame *n* is less than the ST loudness at the previous frame), then

$$S'_n = a_r S_n + (1 - a_r) S'_{n-1}, \quad (3)$$

where *αr* is a constant that is related to *Tr* according to:

$$a_r = 1 - exp(-T_0 / T_r) \quad (4)$$

The values of *αa* and *αr* are 0.045 and 0.033, respectively.

Because of these asymmetric time constants, the increase in ST loudness following an abrupt increase in sound level is more rapid than the decrease in ST loudness following an abrupt decrease in level. As a result, the model predicts differences in loudness changes between rising- and falling-level sounds whose level changes over the same range. The model was run with the stimulus waveform specified at each eardrum.

Initially, it was necessary to decide whether the participants based their judgments on the loudness difference between the start and end of the stimuli or on the ratio of loudness at the start and end. If they did the latter, the loudness changes would be roughly independent of overall level. For example, a change in level from 60 to 75 dB SPL would result in a similar loudness-change judgment to a change in level from 75 to 90 SPL. Clearly, this was not the case; the judged loudness changes increased systematically and markedly with increasing overall level. This suggests that the participants judged loudness differences rather than loudness ratios. In what follows, the predictions are based on estimated loudness differences.

Predictions were generated assuming that the reported change in loudness depends on the difference in ST loudness in sones at a time close to the start of the stimulus and a time close to the end of the stimulus. The predictions depended markedly on the assumed time at which the initial estimate of ST loudness occurred; the exact time of the final estimate of ST had only a small effect. The best fit to the data was obtained assuming that the initial estimate of ST loudness occurred 85 ms after stimulus onset, just before the end of the onset ramp, and the final estimate occurred 100 ms before the end of the stimulus, at the start of the offset ramp, i.e. at 1900 ms. Using these values for the times of the initial and final estimates of ST loudness, the ST loudness change in sones was estimated for each condition. Linear regression lines were then fitted to the data relating predicted change in sones to measured change. This was done separately for the two loudness-change estimation procedures. Scatter plots of the judged loudness changes against the predicted change in sones, together with the fitted regression lines, are shown for each estimation procedure in Figs. 2 and 3.

The fitted lines were used to generate predictions of loudness change for each condition. The predictions are shown in panels A and B of Fig. 1 using asterisk symbols. The correlation of obtained and predicted values was $r(6) = 0.994$ for the 100-point rating scale and $r(6) = 0.980$ for the slider. The differences in loudness change between rising and falling sounds were also accurately predicted.

5. Discussion

The finding that judgments of level change were significantly larger for rising- than for equivalent falling-level tone stimuli is consistent with previous work (Neuhoff, 2001). The pattern of results was similar to that observed by Neuhoff (1998) for their tone stimuli (Fig. 1). Similar asymmetry in loudness judgments has been observed for vowel and violin sounds (Olsen et al., 2010), and noise stimuli (Ponsot et al.,

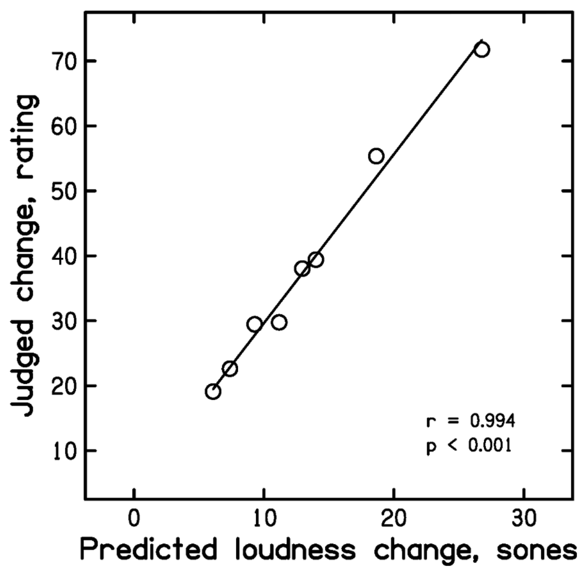

Fig. 2. Scatter plot of the judged loudness changes obtained using the verbal rating procedure against the predicted change in sones, together with the fitted regression line.

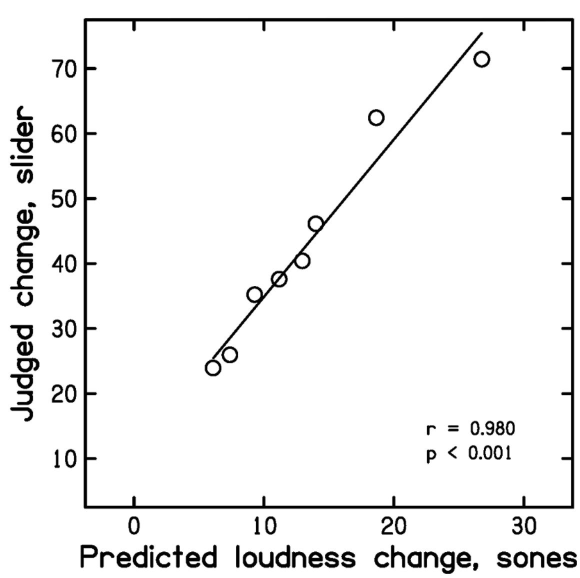

Fig. 3. As Fig. 2 but for loudness-change judgments obtained using the slider.

2015b), and asymmetry has also been reported for rhesus monkeys presented with 1-kHz complex tone stimuli, who gave significantly longer head orientation responses to rising-level than to falling-level sounds (Ghazanfar et al., 2002). Overall, the current results support previous findings of a robust asymmetry for judgments of loudness change for rising compared to falling sounds, especially for tone stimuli. The asymmetry increased with increasing overall level.

The pattern of results was consistent with the predictions of the adaptive perceptual bias theory. However, the results were also accurately predicted by a loudness model for time-varying sounds, suggesting that an adaptive bias is not the only way to explain the observed asymmetry in loudness-change judgments between rising- and falling-level sounds. Taken together with previous findings showing that asymmetries in distance judgments were accurately predicted by the same loudness model (Kolarik et al., 2026), the current results using the loudness model provide an alternative explanation for at least some of the observed asymmetries to that provided by the adaptive bias theory.

The current findings can be compared to those of Ponsot et al. (2015b), who used as stimuli 1-kHz pure tones that rose or fell in level by 15 dB, similar to those used in the current experiments. They asked participants to judge the overall loudness of the stimuli and found that the falling-level stimuli had to be about 4 dB higher in overall level than the rising-level stimuli to achieve equal loudness. The overall loudness of time-varying sounds lasting a few seconds can be predicted using the loudness model from the maximum value of the long-term loudness, which is calculated from the ST loudness, again using an averaging mechanism resembling an automatic gain control system with asymmetric attack and release times. Ponsot et al. found that an older version of the loudness model (Glasberg and Moore, 2002) predicted asymmetry in overall loudness between rising- and falling-level sounds, but the magnitude of the asymmetry was underestimated. The current version of the model also underestimated the asymmetry: the loudness level was predicted to be only about 1 phon higher for rising-level stimuli than for falling-level stimuli changing over the same range of levels. Thus, the current loudness model does not explain all aspects of the loudness asymmetries between rising-level and falling-level sounds.

Most previous studies investigating asymmetries between approaching/receding sound sources (Kolarik et al., 2026; Neuhoff, 1998, 2001; Ponsot et al., 2015a, 2017, 2015b) have changed level rather than changing alternative auditory distance cues such as direct-to-reverberant ratio (Zahorik, 2002) or spectral cues (Kopčo et al., 2011). This raises the question of whether asymmetries occur only when level is changed or whether asymmetry also occurs for perceived motion direction based on any available auditory distance cue. One study altered spectral cues to manipulate whether sounds were judged to approach or recede (Baumgartner et al., 2017). The results provided behavioral and neural evidence for a bias for approaching sounds. Analyses using a loudness model for stationary sounds (Moore et al., 1997) showed that there were only very small differences in loudness between the sounds judged as close and the sounds judged as far away. These findings demonstrate that changes in alternative distance cues to sound level can elicit a looming bias. However, this study used only sound sources with a maximum simulated distance of 1.5 m from the listener. Further work is needed to investigate whether alternative distance cues to level can produce a looming bias for greater test distances.

Given that level is the predominant distance cue used by humans (for reviews of the various auditory distance cues available, see Kolarik et al. (2016) and Zahorik et al. (2005)), it seems likely that the loudness model used here will give accurate predictions of any asymmetry for the majority of naturalistic environments. However, further investigations are needed to establish the extent to which loudness models can explain biases for approaching sounds in environmental situations that differ in the availability of different types of distance cues.

Despite the numerous reports of loudness asymmetries for rising versus falling level sounds (Neuhoff, 1998, 2001; Ponsot et al., 2015a, 2017, 2015b), we are not aware of studies that have investigated the effects of sensory loss on the magnitude of the asymmetry. The current findings demonstrate that asymmetry is observed across different response modes, and suggest that future investigations of the effects of visual loss on judgments of loudness change could use verbal or tactile response modes. Previous work has shown that full vision loss affects auditory distance judgments, resulting in a compressive internal representation of auditory distance (Kolarik et al., 2017). In addition, greater severity of visual loss was associated with larger judged distance of sounds (Kolarik et al., 2020), and totally blind participants showed greater accuracy in time-to-arrival judgments for approaching sounds than sighted participants (Schiff et al., 1990). Given the importance of accurate spatial information for visually impaired individuals using sound to anticipate whether they are at risk of colliding with approaching objects, future studies could investigate whether the magnitude of asymmetry for rising- versus falling-level sounds is affected by different severities of visual loss. Future research could also investigate asymmetry in loudness judgments for individuals with hearing loss who are affected by loudness recruitment, where the rate of growth of loudness level with increasing sound level is larger than for individuals with normal hearing (Moore et al., 1996).

6. Conclusions

The current findings showed that asymmetries in loudness-change judgments for rising-level and falling-level sounds occurred for tone stimuli, the asymmetry increasing with increasing overall level. The asymmetry was similar for verbal and tactile response modes and was accurately predicted by a loudness model for time-varying sounds. This suggests an alternative to the adaptive perceptual bias theory previously put forward to explain loudness judgment asymmetry. Further work testing loudness judgments for a wider variety of stimuli could be undertaken to assess the accuracy of the predictions of the loudness model across a wider variety of experimental conditions.

CRediT authorship contribution statement

Andrew J. Kolarik: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Anna Koblitz:** Writing – review & editing, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Brian C.J. Moore:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Formal analysis, Conceptualization. **Ian van der Linde:** Writing – review & editing, Supervision, Methodology, Conceptualization. **William Campbell:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Shahina Pardhan:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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