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Looming sounds as warning signals: The function of motion cues

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ABSTRACT

Sounds with increasing intensity can act as intrinsic warning cues by signalling that the sound source is approaching. However, intensity change is not always the dominant motion cue to a moving sound, and the effects of simple rising intensity sounds versus sounds with full three dimensional motion cues have not yet been directly compared. Here, we examined skin conductance responses, phasic alertness, and perceptual and explicit emotional ratings in response to approaching and receding sounds characterised either by full motion cues or by intensity change only. We found a stronger approach/recede effect in sounds with full motion cues for skin conductance response amplitude, suggesting sustained mobilisation of resources due to their greater saliency. Otherwise, the approach/recede effect was comparable in sounds with and without full motion cues. Overall, approaching sounds elicited greater skin conductance responses and phasic alertness, and loudness change was estimated higher. Also, they were rated as more unpleasant, potent, arousing and intense, and the probability of such sounds to signal a salient event or threat was rated higher. Several of these effects were modulated by sex. In summary, this study supports the suggestion that intensity change is the dominant motion cue mediating the effects of approaching sound sources, thus clarifying the interpretation of previous studies using such stimuli. Explicit emotional appraisal of such sounds shows a strong directional asymmetry and thus may reflect their implicit warning properties.

1. Introduction

Detecting an approaching object can be critical for survival. From an evolutionary perspective, it has therefore been argued that a perceptual bias for approaching (or *looming*) sounds in preference to receding sounds would be of selective advantage (Neuhoff, 2001). Evidence for such a bias comes from studies showing that the distance or time-to-arrival of looming sound sources is underestimated by humans, both in absolute terms and compared to receding sounds (Neuhoff, 2001; Neuhoff et al., 2009; Schiff and Oldak, 1990).

Moving sound sources provide a vast array of specific acoustic cues. Among them are binaural cues such as interaural level and time differences, and monaural cues such as overall intensity change, Doppler shift and atmospheric filtering. It has been suggested that an overall increase in intensity is dominant for inferring the position of an approaching sound source (Rosenblum et al., 1987), at least at slow sound source speed (i.e. 10 m/s, Lutfi and Wang, 1999). Since it is easier to quantify this intensity increase than the other complex characteristics of approaching sound sources, a number of studies have used diotic stimuli with rising sound intensity as a model for looming sound sources. Loudness change in such sounds is overestimated (Neuhoff, 1998, 2001). An intensity increase of 15 dB over 2 s elicits a stronger autonomic orienting reaction than an intensity decrease of the same magnitude, quantified as phasic skin conductance reaction [SCR] 4–5 s after stimulus onset, and heart rate deceleration 2–3 s after stimulus onset (Bach et al., 2008). In this context, enhanced SCR has been interpreted as reflecting mobilisation of energetic resources (see also Barry, 1987). At the same time, rising intensity appears to accelerate reaction times [RTs] to subsequent auditory targets (Bach et al., 2008). This indicates enhanced phasic alertness and resembles responses to experimentally learned warning cues (Roberts et al., 2006).

However, the heavy reliance on simple intensity change to examine putative auditory motion perception can be called into question. For example, at higher sound source speeds (i.e. 50 m/s), motion cues other than overall intensity change can be dominant (Lutfi and Wang, 1999). Thus, it is possible that the perceptual bias for approaching sounds is not *only* due to the differential effects of simple rising and falling intensity. The approach/recede effects found in previous work could be even *more* pronounced when sounds contain full motion cues and are therefore easier to characterise in terms of speed and position. However, the opposite prediction might also be true. In neuroimaging studies, stimulus relevance has been found to be represented in the amygdala (Sander et al., 2003), and the

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amygdala also responds to looming sounds (Bach et al., 2008). There is some evidence that such amygdala responses are increased when potentially relevant stimuli lack precise information about their relevance (Whalen, 1998; see also Whalen et al., 2001). Amygdala responses are supposed to reflect stimulus saliency in this context, and are related to phasic SCRs (Laine et al., 2009; Williams et al., 2001). Sounds containing intensity change as only motion cue lack precise motion information. Hence, one might expect stronger SCRs, and possibly perceptual bias and phasic alertness to approaching sounds that are characterised by simple intensity change only, while for receding sounds there may be no difference as these sounds might be perceived as bearing little relevance anyway.

In the present study, we compared complex full-cue binaural approaching/receding sounds to diotic rising/falling intensity sounds. In this 2 × 2 factorial design, we expected differential effects of motion cues in the interaction sound source direction × motion cues. One aim of this study was to help interpret the results of previous experiments. Thus, stimuli and dependent measures were chosen to be comparable with those of previous studies. In a first experiment, we measured ratings of loudness change to examine the magnitude of the perceptual bias in each condition. In the second experiment, we measured SCR and RTs to subsequent targets as measures of the warning properties of each type of sound. This was conducted on a sample independent from the first experiment in order to prevent effects of repeated exposure to the stimuli. We also sought to examine how participants would explicitly characterise approaching and receding sounds. Recent work has argued that the perceptual bias for approaching sounds could be due to perceptual characteristics alone (Grassi and Darwin, 2006). Thus, we used a novel measure to more explicitly assess the significance of these sounds by collecting emotional ratings. We hypothesised that these ratings would reflect the implicit warning properties of approaching sounds. Finally, because there is evidence for effects of sex on the perceptual bias (Neuhoff et al., 2009), we included this as additional factor into all analyses.

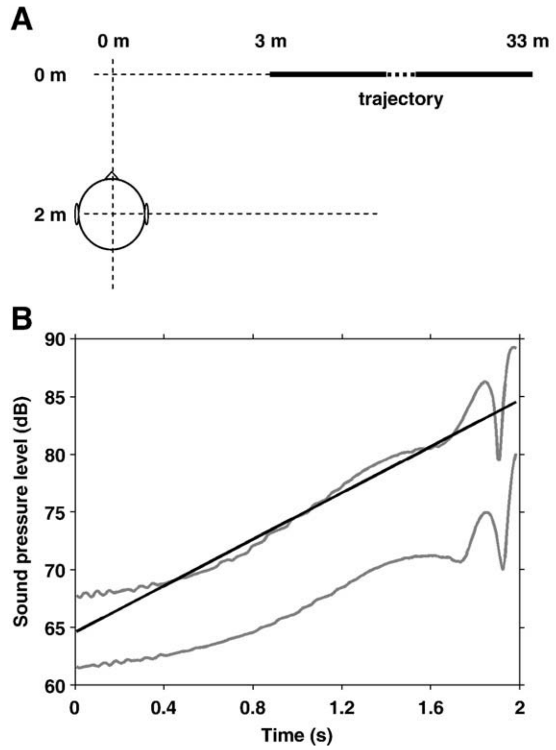

Fig. 1. Sound stimuli for both experiments. A: Trajectory (solid line) of the approaching/receding sounds in relation to the listener's head and the interaural axis. All distances are expressed with respect to the intersection of the trajectory with the midline of the listener's head. Note that the sound source was elevated 0.5 m above ground, which is not shown in the figure. B: Sound pressure level in dB for diotic sounds with partial motion cues (i.e. increasing intensity, black line) and dichotic sounds with full motion cues (separate grey lines for each ear). Initial and terminal sound pressure level was matched for the two sounds (averaged across both ears), while overall sound pressure level was higher for sounds with partial motion cues. dB values apply to sounds used in experiment 2. Sounds in experiment 1 differed from these only in overall intensity (see text for details).

2. Methods

2.1. Design and participants

Experiments followed a 2 (*sound source direction*: approach/recede) × 2 (*motion cues*: full motion cues/intensity change only) × 2 (*sex*: male, female) [× 2 (*target modality*: auditory, visual)] factorial design. 44 healthy individuals from the general population (22 males, 22 females, age mean ± standard deviation: 27.5 ± 7.0 years) took part in experiment 1. 24 healthy university students (12 males, 12 females, age mean ± standard deviation: 24.8 ± 3.7 years) participated in experiment 2. All participants gave written informed consent, and both experiments were approved by the respective local ethics committee.

2.2. Stimuli for both experiments

Binaural stimuli with full motion cues were constructed as described previously (Neuhoff et al., 2009). As Fig. 1A shows, they consisted of a virtual sound source moving on a trajectory that was parallel to the listener's interaural axis and situated at 2 m distance from the listener who was facing the trajectory. The sound source began 33 m from the intersection of the trajectory with the midpoint of the listener's head, approached at 15 m/s, and arrived at 3 m distance from the intersection of the trajectory with the midpoint of the listener's head (see Fig. 1A), and vice versa for receding sounds. The sound source was elevated 0.5 m above ground. Approach side was constant for each participant and was balanced across participants. The sound source was a square wave with a fundamental frequency of 400 Hz, and a sampling rate of 44.1 kHz. The simulation yielded a realistic three-dimensional sound source approach that included absolute delay (to account for the speed of sound and the changing distance between the listener and the source), Doppler shift, atmospheric filtering, gain attenuation due to atmospheric spreading, ground reflection attenuation, and head-related transfer function (HRTF) from the MIT KEMAR data set (Gardner and Martin, 1995). Approaching and receding sounds with full motion cues were created separately.

Diotic stimuli were created by modulating the amplitude of 400 Hz square waves. Initial and terminal sound pressure level of diotic stimuli was matched to sound pressure level of binaural stimuli with full motion cues (averaged across both ears). Diotic intensity increased linearly, thus making the overall sound pressure level for the entire stimulus somewhat higher for the simple intensity change sounds than for those with full motion cues (see Fig. 1B). Receding diotic sounds were created by reversing approaching diotic sounds in time.

Initial and terminal ramp duration of all sounds was 10 ms to avoid possible startle responses to sound onset.

2.3. Procedure and apparatus

2.3.1. Experiment 1 (intensity change ratings)

Each of four stimuli was presented three times via headphones (PX-660 Pro Luxe, Fujikon, Hong-Kong, China) with initial/terminal sound pressure levels at 50/70, 55/75, and 60/80 dB for approaching, and vice versa for receding sounds. Stimulus order was randomised. Participants were asked to “Please rate [the] loudness change” on a horizontal visual analogue scale (VAS), anchored at the ends with the words "no change", and "large change". Instructions specifically stated that "we are interested only in the loudness change, not in the loudness itself". The experiment was programmed in Cogent (Version 2000v1.25; www.vislab.ucl.ac.uk/Cogent) on Matlab (Version 6.5; MathWorks; Natick MA; USA).

2.3.2. Experiment 2 (SCR and RT)

A pseudo-randomized sequence of 200 stimuli (50 per category) with initial/terminal sound pressure levels at 65/85 dB for approaching sounds (and vice versa for receding sounds) was presented via headphones (SBCHP800/00, Philips, Amsterdam, Netherlands). We measured SCR and RT at interleaved trials. Thus, each stimulus was randomly followed either by a visual target (40 trials, or 20%), an auditory target (40 trials, or 20%), or no target (120 trials, or 60%, see Fig. 2). Targets were delivered 100 ms after the stimulus had ended. Auditory targets were pure diotic sine tones (1200 Hz, 85 dB, 100 ms duration). Visual targets were shown as red rhombi on a computer screen (0.5° visual angle, 100 ms duration). Participants were tasked to respond to any auditory or visual target that occurred after the auditory stimulus by pressing a button with their dominant hand (Serial Response Box; Psychology Software Tools; Pittsburgh PA; USA). Stimulus onset asynchrony was 8 ± 1 s, thus leaving an inter-trial interval of about 6 ± 1 s. The experiment was programmed in E-Prime (Version 1.1.4.4, Psychology Software Tools; Pittsburgh PA; USA). For the analysis of reaction times, only correct responses within 1000 ms were included. For the analysis of SCR, only the 120 trials that were not followed by visual or auditory targets were included, as to avoid motor action obscuring autonomic responses. After skin cleansing with 70% isopropyl alcohol, skin conductance was recorded on thenar/hypothenar of the non-dominant hand using 8 mm Ag/AgCl cup electrodes and 0.5%-NaCl electrode paste (EC-33 Skin Conductance Electrode Paste, PAR Medizintechnik, Berlin, Germany). Constant voltage of 0.5 V was provided by an integrated skin conductance pre-amplifier (Model 2701; Bioderm; Morro Bay CA; USA). The signal was digitally converted with 1000 Hz sampling frequency (MacLabs4, ADInstruments; Bella Vista NSW; Australia), digitally bandpass-filtered (cut off frequencies: 0.1 Hz and 5 Hz) and recorded (PowerLab Chart 4.2.3, ADInstruments). After visual inspection (Vision Analyzer Version 1.05; Brain Products; München; Germany), skin conductance response magnitude (SCR) was calculated as mean SCR between 4 and 5 s after sound onset, corrected for 1 s baseline before sound onset (Bach et al., 2008). We analysed SCR amplitude for trials where an SCR above an amplitude criterion was elicited (0.01 µS, 0.02 µS, or 0.05 µS). These three thresholds led to equivalent results, and we only report the data using an amplitude criterion of 0.01 µS. No effects were found in measures of response rates, the results of which are therefore omitted for the sake of brevity. All SCR measures were approximately normally distributed (all $p > .15$). At the end of experiment 2, participants were asked to rate all stimuli on horizontal VASs. The ends of these scales were anchored with one anchor word each. The following emotional dimensions were rated (participants' description and left/right anchor words in brackets): valence (pleasantness: unpleasant–pleasant), potency (power: weak–strong), arousal (activation: calming–activating), and intensity (intensity: little intense–very intense). In addition, participants were asked to "imagine that you hear this sound in every day life. How likely is it that this sound will be followed by a significant event?" (saliency), and "how likely is it that this sound will be followed by a threatening event?" (threat). A stimulus was presented with one dimension to rate, and it was fully played before the rating could be given. Stimuli and dimensions to rate appeared in random order.

2.4. Data analysis

Data analysis was carried out in SPSS (Version 12, Chicago IL, USA).

3. Results

3.1. Experiment 1: ratings of loudness change

Ratings of loudness change were significantly larger for approaching than for receding sounds (see Fig. 3A; with and without full motion cues; $F_{1, 42} = 19.5$; $p < .001$). Also, they were larger for sounds with intensity change only than for their counterparts with full motion cues (regardless of direction; $F_{1, 42} = 13.4$; $p = .001$). In addition, male participants rated loudness change generally larger than female participants, regardless of sound source direction or motion cues ($F_{1, 42} = 6.5$; $p < .05$). There was no sound source direction × motion cues interaction.

3.2. Experiment 2: skin conductance responses

Fig. 3B (left graph) shows SCR magnitude (i.e. the averaged SCR across all trials, including trials where no above-threshold SCR was elicited). It can be seen that SCR magnitude was larger for approaching than for receding sounds (with and without full motion

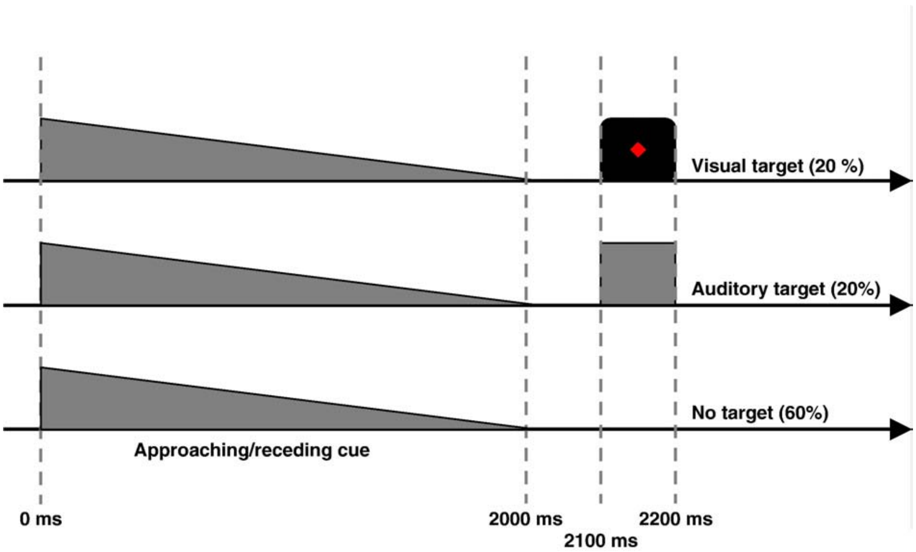

Fig. 2. Experiment 2: 100 ms after the offset of an approaching or receding sound, a visual (20%), or auditory target (20%) was presented for 100 ms, or no target was presented (60%). SCRs were analysed during no-target trials.

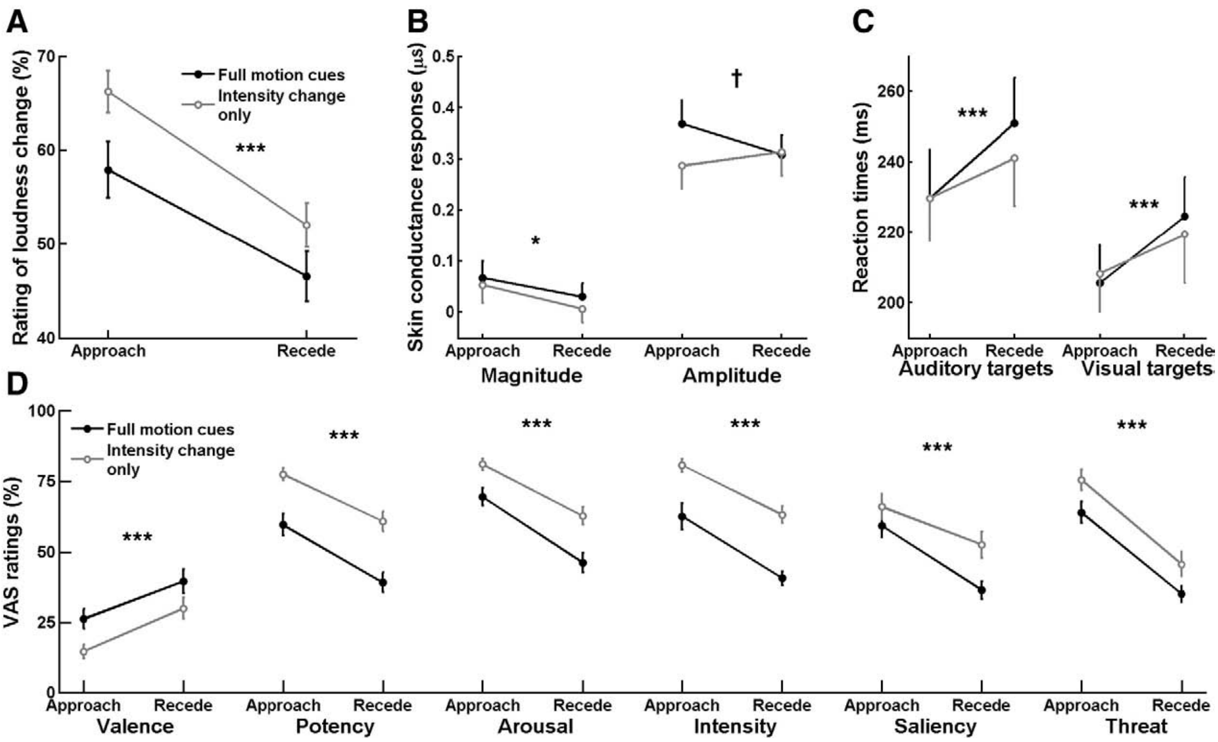

Fig. 3. Responses to approaching and receding sounds, characterised either by full motion cues or by intensity change only. A: Ratings of loudness change. B: Magnitude of the skin conductance response in µS, averaged across all trials (left) and amplitude averaged across trials where the response exceeded a threshold of 0.01 µS. C: Reaction times in ms to subsequently presented auditory (left) and visual (right) targets. D: Explicit emotional ratings in % on a visual analogue scales for valence (unpleasant–pleasant), potency (weak–strong), arousal/activation (calming–activating), global intensity (little intense–very intense), and probability of the sound indicating a significant event (saliency) or a threat. All values are given as mean ± standard error of the mean. Main effect sound source direction: *p<.05 ***p<.001. Interaction sound source direction × motion cues: †p<.05.

cues; $F_{1,\ 22} = 5.2$; $p < .05$). There was no effect of motion cues or sex and no interaction effect ($F_{1,\ 22} = 0.2$; $p = .70$). Analysis of trials where an above-threshold SCR was elicited conveys additional information (see Boucsein, 1992; see right graph in Fig. 3B). In these trials, a higher SCR amplitude for approaching than receding sounds could only be shown for sounds with full motion cues but not for sounds with intensity change (sound source direction × motion cues interaction; $F_{1,\ 21} = 6.6$; $p < .05$). This interaction was additionally modulated by sex (sound source direction × motion cues × sex interaction: $F_{1,\ 21} = 8.2$; $p < .01$). That is, men and women did not differ with regard to sounds with full motion cues ($F_{1,\ 21} < 1$; *n.s.*), but in response to intensity change only stimuli, women had a weaker direction effect than men ($F_{1,\ 21} = 4.7$; $p < .05$).

3.3. Experiment 2: reaction times

Targets appeared after a proportion of approaching and receding sounds, and RTs to these targets served as measure for phasic alertness (see Fig. 3B). RTs were faster after approaching than after receding sounds (with and without full motion cues; $F_{1,\ 22} = 27.6$; $p < .001$) and faster to visual than to auditory targets ($F_{1,\ 22} = 15.3$; $p = .001$). No other significant main or interaction effects were observed.

3.4. Experiment 2: emotional ratings

After the phasic alertness task, participants gave explicit emotional ratings of the approaching and receding sounds in order to characterise their emotional significance (see Fig. 3D and Table 1). Approaching sounds (with and without full motion cues) were rated as more unpleasant, more potent, more arousing, more intense, more salient and more threatening than receding sounds. In comparison to sounds with full motion cues, intensity change only sounds were rated as less pleasant, more potent, more arousing, more intense, more salient and more threatening, regardless of direction. The approach > recede effect in potency and intensity was higher for women than for men. There was no sound source direction × motion cues interaction.

4. Discussion

This study sought to determine whether the presence of full motion cues enhances or attenuates the warning properties of looming sounds. A key finding is the higher SCR amplitude in approaching sounds with full motion cues, while in all other measures, the two types of sounds were rather comparable. As an additional and novel result, explicit

Table 1
Explicit emotional ratings in experiment 2.

	Sound source direction	Motion cues	Sex	Direction × motion cues	Sex × direction	Sex × motion cues	Sex × direction × motion cues
Valence	18.4***	22.9***	2.0	< 1	<1	<1	<1
Potency	27.7***	68.1***	1.4	< 1	<1	4.5*	<1
Arousal	43.6***	39.0***	<1	<1	<1	3.2	<1
Intensity	33.5***	74.2***	1.8	<1	1.2	9.0**	<1
Saliency	16.6***	24.7***	1.9	2.5	<1	1.2	<1
Threat	56.8***	17.2***	<1	1.3	<1	<1	1.0

Results from the 2 (sound source direction) × 2 (motion cues) × 2 (sex) — ANOVA. All values are F-values with $df = 1, 22$. Descriptive data is described in the text and shown in Fig. 3D.
*p<.05, **p<.01, ***p<.001.

emotional ratings for approaching and receding sounds differed on all dimensions, pointing towards negative valence and greater significance of approaching sounds.

4.1. Effect of motion cues on responses to sound source direction

This is the first study to directly compare approaching and receding sounds with and without full motion cues in order to align previous studies using rising sound intensity (Bach et al., 2008; Cappe et al., 2009; Ghazanfar et al., 2002; Maier et al., 2004, 2008; Maier and Ghazanfar, 2007; Neuhoff, 1998; 2001; Seifritz et al., 2002) with those using stimuli containing full motion cues (Neuhoff, 2001; Neuhoff et al., 2009; Schiff and Oldak, 1990). Looming sounds might be easier to detect and thus be more salient when they contain full motion cues. On the other hand, it has been argued that relevant stimuli might be more salient when they lack some relevance information (Whalen, 1998). It appears that in most of our measures, the effects of looming sounds are comparable for full motion cues and intensity change only, thus reflecting the dominance of intensity change over other motion cues (Lutfi and Wang, 1999; Rosenblum et al., 1987). The greater SCR amplitude for looming sounds with full motion cues is in keeping with the idea that additional motion cues render looming stimuli more salient. No support was found for the opposite hypothesis that a relative lack of relevance information indicates stimulus saliency. This latter hypothesis was derived from neuroimaging data on amygdala responses in facial expression perception (Whalen et al., 2001) and fear conditioning (Whalen, 1998). One might argue that behavioural and psychophysiological responses do not necessarily reflect amygdala activity. Another explanation for the present finding is that such effects of missing information might be specific to the paradigms mentioned above. In fact, the notion of enhanced amygdala responses to ambiguous cues (Whalen, 1998) has recently been qualified with respect to lack of information in aversive outcome prediction (Bach et al., 2009).

SCR amplitude was derived from trials where an SCR was generated. It might therefore allow quantification of resource allocation once this process is started. Our data suggest that once an orienting reaction is initiated after hearing sounds with intensity change only, the amplitude of this response does not differ between approaching and receding sounds. On the contrary, after sounds with full motion cues, reaction amplitude is dependent on direction. One explanation for this finding relates to the temporal structure of the underlying initial appraisal. Since intensity change can constitute the dominant motion cue (Lutfi and Wang, 1999; Rosenblum et al., 1987), it is plausible to assume that it is detected more easily than other motion cues (or their absence). Initial appraisal of looming sounds might therefore only depend on intensity change. However, further analysis might classify approaching and receding sounds with partial motion cues as equally (in)significant. Therefore, once an orienting reaction is initiated, it would no longer distinguish sound source direction. On the other hand, if the analysis of approaching sounds with full motion cues continues, they might more likely be identified as significant, and might therefore lead to sustained mobilisation of energetic resources (Barry, 1987).

The effect of motion cues on SCR amplitude was mainly carried by female participants. The small sample size did however not allow further investigation of sex differences. Previous work has suggested an effect of sex on perceptual bias in response to approaching and receding sounds (Neuhoff et al., 2009; Schiff and Oldak, 1990), however we know of no work to date investigating the effects of sex on the perception of specific auditory motion cues.

4.2. Responses to sound source direction

All of our measures were influenced by sound source direction, thus extending results from previous studies using intensity change as the only motion cue (Bach et al., 2008; Neuhoff, 1998) to sounds will full motion cues. Although it has been suggested that the overestimation of loudness change in approaching sounds might be simply due to perceptual factors (Grassi and Darwin, 2006), the strong effect on physiological measures is evidence for the biological significance of approaching sounds. This is particularly evident in connection with explicit emotional ratings. On all dimensions of the semantic differential, that is, valence (unpleasant–pleasant), potency (weak–strong) and arousal (calming–activating), these ratings clearly distinguished between approaching and receding sounds and may suggest that the biological significance of approaching sounds is something that humans appear to be consciously aware of, and that might be integrated into reasoning and decision-making.

In a previous study, effects on RTs were modality-specific and only occurred in response to auditory, but not visual targets (Bach et al., 2008). Here, in an almost identical paradigm, we observed the same phasic alertness response to auditory and visual targets which is in keeping with similar cross-modal effects of other auditory warning stimuli such as emotional prosody (Brosch et al., 2008). A possible explanation for the difference between the present and our previous study refers to the precise spatial location of the visual stimulus with respect to the apparent approaching point of the looming sounds. In the present experiment, the visual target occurred in the centre of vision, and close to the apparent trajectory of the looming stimulus, whereas it was positioned more peripherally in the previous experiment. Auditory and visual stimuli occurring within ~3° spatial angle and ~100 ms can be perceived as belonging to the same source (Lewald et al., 2001). Thus, it might be that the phasic alertness increase for visual targets is dependent on central vision, or on auditory–visual integration. This is also reflected in faster mean RTs to visual targets in the present as compared to the previous study. Also, overall RTs were faster for visual than for auditory targets, which might relate to the viewpoint that the auditory system mainly serves to gather information about the presence of unseen sound sources while the visual system then extracts precise information about these sound sources (Guski, 1992; Schiff and Oldak, 1990). This is in keeping with the recent finding that auditory attention engages the primary visual cortex (Cate et al., 2009). Consequently, upon hearing a sound, attention could be shifted to the visual modality which might explain faster RTs.

An alternative explanation for main effects of sound source direction relates to the terminal amplitude of approaching and receding sounds that might have different impact on our dependent measures regardless of apparent sound source motion. Previous studies have established that the presence/absence of a prepulse influences decision criterion and EEG measures (but not reaction times) in an auditory discrimination task (Kroner et al., 1999; Schall and Ward, 1996); however the influence of prepulse intensity on the dependent measures used in the present study has not been investigated such that we cannot rule out this explanation although there is no direct support from the literature.

4.3. Responses to motion cues

We found strong main effects of motion cues in measures for phasic attention, perceptual bias, and explicit emotional ratings. Due to the construction of the stimulus set with fixed initial and terminal sound pressure level, the overall sound pressure level of sounds with full motion cues was lower than for intensity change only sounds. This might explain stronger responses towards intensity change only sounds regardless of direction of change.

5. Conclusions

We gathered responses to approaching and receding sounds as signalled by full motion cues, or by intensity change alone. The presence of full motion cues modulated SCR amplitude to approaching as compared to receding sounds, which might reflect sustained mobilisation of energetic resources when full motion cues were present. In all other measures, both types of sounds were comparable with respect to the effect of sound source direction. No support was found for the hypothesis that lack of relevance information might render looming stimuli more salient. As an additional finding, explicit emotional ratings strongly depended on sound source direction and thus appear to reflect the implicit warning properties of these sounds on an explicit, conscious level.

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