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An Evaluation of the Effect of Auditory Emotional Stimuli on Interval Timing

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Abstract

Emotions modulate cognitive processes, including those involved in the perception of time. A number of studies have demonstrated that the emotional modulation of interval timing can be described in terms of an attentional or an arousal-based mechanism, depending on the exact task setup. In this paper, two temporal generalization experiments with auditory emotional stimuli as distractors are presented. These experiments are modeled after the work by Lui et al. (*PLoS One*, 2011, *6*, e218292011) who, using visual distractors, provided evidence for an attentional account of emotion-regulated modulation of the perception of time. Experiment 1 replicates the findings of Lui et al., and thus generalizes their work to auditory stimuli. However, Experiment 2, in setup highly similar to Experiment 1, failed to find any effects of emotional modulation on interval timing. These results indicate that emotional effects on interval timing, although often reported, might not be as ubiquitous as earlier research has (implicitly) suggested.

Keywords

Interval timing, time perception, emotion, auditory stimuli, pacemaker–accumulator models, attention vs. arousal, temporal modulation

1. Introduction

Emotional states have a strong impact on cognitive processes and the resulting behaviors (for reviews, Dolan, 2002; Schirmer, 2014), although the exact mechanisms underlying this connection are still topics of discussion (e.g., Pessoa, 2008; Zeelenberg et al., 2006). One line of work focuses on how emotional states influence the perception of time (e.g., Droit-Volet, 2013; Droit-Volet & Meck, 2007; Fayolle et al., 2013, 2015; Gan et al., 2009; Gil & Droit-Volet, 2009; Lui et al., 2011; Meck & MacDonald, 2007; Noulhiane et al., 2007), with different research groups

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proposing different mechanisms. Interestingly, all these mechanisms have links to the influential pacemaker–accumulator framework of time perception.

The pacemaker–accumulator model of time perception, often formalized in terms of the Scalar Timing Theory (e.g., Church, 2003; Gibbon et al., 1984; see Van Rijn et al., 2014 for a recent review) is based on four different components; a pacemaker, an accumulator, a memory store and a comparator. The pacemaker emits a steady stream of pulses, and as soon as the start of a to be timed event has been perceived, the accumulator starts to accrue pulses. When the to-be-timed interval has finished, the number of accrued pulses is compared to duration representations stored in long-term memory in order to make an adequate temporal response. The Scalar Timing Theory has provided a thorough theoretical framework in terms of which many temporal phenomena can be interpreted. By embedding this theory in a general cognitive architecture (Taatgen et al., 2007; Van Rijn & Taatgen, 2008), computational models of complex cognitive tasks can now include a principled account of the temporal aspects of these tasks (e.g., Kujala & Salvucci, 2015; Moon & Anderson, 2013). Moreover, this integration allows to further constrain timing theories (Taatgen & van Rijn, 2011).

An important addition to the pacemaker–accumulator theories is the 'attentional gate' proposed by Zakay and Block (1995). This metaphorical 'gate', located between the pacemaker and the accumulator, influences the speed of accrual in the accumulator, with a partly-closed gate resulting in slowed accumulation of pulses. As it is assumed that the gate is opened as a function of the amount of attention directed to the timing task, this 'attentional gate' model can be used to describe attentional influences on time processing. Thus, when attention has to be divided between the to-be-timed stimulus and a secondary task or event, the subjective perception of time will be affected as fewer pulses accumulate per unit of objective time (but see Taatgen et al., 2007, for a paradigm in which attentional modulation does not influence the perception of time and Buhusi & Meck, 2009, for alternative views of attentional time sharing).

Based on the pacemaker–accumulator model, two explanations for emotion-induced temporal distortions have been proposed. The first explanation refers to the role of *attention* for temporal processing (e.g., Schirmer, 2011), and cites evidence that individuals more readily attend to emotional than to neutral stimuli. Moreover, this explanation holds that emotions influence the attentional gate, thereby changing the number of accumulated pulses such that subjective time becomes longer or shorter. Specifically, a stimulus will be perceived as longer if it is emotional as compared to neutral. However, a neutral stimulus that is timed on the backdrop of distractors, will be perceived as shorter if distractors are emotional as compared to neutral.

The second explanation of emotion-induced temporal distortions involves *arousal* (e.g., Droit-Volet & Meck, 2007). According to this account, increased arousal leads to an increased pacemaker rate. Compared to neutral stimuli, emotional stimuli result, by influencing the arousal level, in a greater number of accumulated pulses and are, therefore, perceived as longer. Moreover, neutral stimuli timed on the backdrop of distractors are perceived as longer if distractors are emotional as compared to neutral. In addition, based on higher arousal levels, the onset of emotional stimuli could be perceived more efficiently or faster than the onset of neutral stimuli, also resulting in an increased perceived duration.

Although there have been many studies about how emotions affect the processing of time, the findings of these studies are inconsistent, with some studies interpreted as evidence for an attentional modulation and others for an arousal modulation, or for a combination of both. For example, Lui et al. (2011) explored the role of visual emotional and neutral distractors in the timing of neutral events using a temporal generalization paradigm. Subjects were shown two neutral stimuli for which they had to indicate whether the second stimulus (S2) was presented for a longer or shorter time period than the first stimulus (S1), which had a constant duration. Emotion was manipulated by presenting a task-irrelevant picture, either emotional or neutral, in between S1 and S2. Across a number of experiments, Lui and colleagues found that, on average, S2 was perceived as shorter when preceded by an emotional as compared to a neutral distractor. In line with the attention modulation reasoning outlined above, this suggests that greater attention directed to the encoding of the emotional stimulus, presented just before the timing stimulus, comes at a cost of attention directed to the processing of time (for similar results, see this issue Lake et al., 2016).

Droit-Volet et al. (2004) provided evidence for an arousal-based modulation of the perception of time. Using a temporal bisection task with emotional faces as stimuli reflecting the durations, they found a systematic overestimation of time for the emotional faces (i.e., expressing anger, happiness or sadness) compared to the neutral faces. This effect has been replicated across many studies (e.g., this issue Droit-Volet et al., 2016; Eberhardt et al., 2016). In addition, Noulhiane et al. (2007) found evidence for an arousal modulation of time perception when stimuli were presented in the auditory domain. In their sound reproduction task, subjects were more likely to overestimate the duration of an emotional tone, as reflected in a lengthened reproduction, than a neutral tone.

Due to the high variety in experimental designs, it remains unclear whether there is one modulation that, in general, accounts for emotion-induced temporal distortion, or whether the modulation is perhaps task or domain specific. To address the issue of generalizability, the present study adapted the paradigm of Lui et al. (2011), who argued that emotional effects on time perception could be explained by an attention modulation. Instead of their visual distractor stimuli, the experiments reported here used auditory distractor stimuli. Although a large number of earlier studies have indicated that stimuli presented in the auditory domain might evoke slightly different timing processes than stimuli presented in the visual domain (e.g., Grondin, 1993; Grondin & Rousseau, 1991; Penney et al., 2000, 2014; Van Wassenhove et al., 2008), these studies generally acknowledge that the main temporal processes are in place irrespective of the modality used. Therefore, effects should be alike when participants are presented negative valence distractors in the auditory and in the visual domain. To increase the emotional response, participants were conditioned to associate a colored square with a neutral auditory stimulus, and a differently colored square with a negative auditory stimulus (see, for a similar setup, Lake et al., 2016). By presenting these cues probabilistically before the auditory distractor stimulus, we expected to increase the emotional response to the auditory distractors, as earlier work has shown that uncertainty during anticipation increases the neural responses to emotional stimuli (Sarinopoulos et al., 2010).

2. Experiment 1

2.1. Methods

2.1.1. Participants

Twenty naïve participants (mean age = 21.25; SD = 2.90; range 18–19; 11 male) were recruited from the student participant pool of the Department of Psychology at the University of Groningen and were offered partial course credits in exchange for participation. All participants reported having normal or corrected-to-normal sight and normal hearing. Ethics approval was obtained from the Psychology Ethics Committee of the University of Groningen.

2.1.2. Materials and Procedure

The experiment, implemented in E-Prime v2, consisted of four blocks: two practice blocks, one conditioning/sound-rating block and one experimental block. In the first two practice blocks, participants were familiarized with the temporal generalization task. This task consisted of two successively presented visual stimuli (S1 and S2), and participants were instructed to judge whether S2 was presented for a longer or shorter duration than the earlier presented S1. The stimuli were filled black circles with a diameter of nine millimeters presented against a white background in the center of a computer screen (a 22″ IIlyama Vision Master Pro 513 monitor set to a resolution of 1280 × 1024, 85 Hz), which was located at an approximate distance of 60 cm from the participant. Participants responded by pressing the '*z*' key to indicate that S2 was perceived as shorter, and 'm' to indicate that S2 was perceived as longer than S1. For a schematic representation of the trial setup, see Fig. 1.

The first practice block consisted of twelve trials in which S1 was presented for 1200 ms and S2 for 800, 1000, 1400 or 1600 ms (each S2-duration was presented three times, in random order). After familiarization with the basic structure of the temporal generalization task using these durations, the second practice block commenced in which participants were presented the same S2 durations as presented during the experiment proper (i.e., 1040, 1120, 1280 or 1360 ms, with each duration presented ten times, in random order).

The purpose of the third block was to elicit an association between visual cues and the emotional valence of sounds, and to obtain ratings of the valence of these sounds. On each trial of this block, participants saw a single blue or green square of nine by nine millimeters in the center of the computer screen and heard a prerecorded sound (played over headphones at ~ 65 dB) of, respectively, a negative or neutral event. A total of eighteen different sounds were used. An initial sound set, provided by A. Schirmer (National University of Singapore), was supplemented with sounds collected from an online database (www.freesound.org). From these sounds nine were selected by the authors

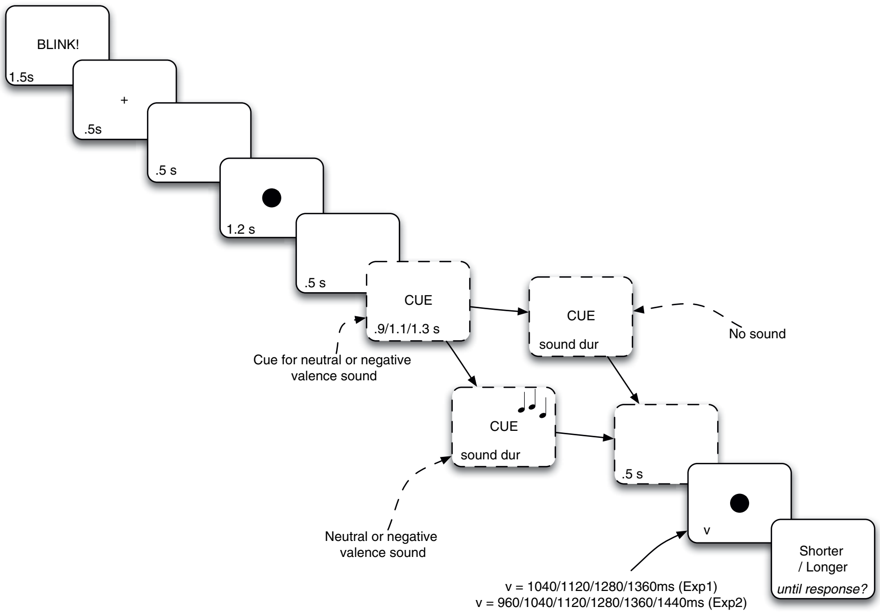

Figure 1. The trial setup of the temporal judgment task in Experiments 1 and 2. See text for further details.

as neutral and nine others as negative (see Table 1 for a complete overview). Although care was taken to select sounds of similar duration, the naturalistic nature of the stimuli hampered balancing of both groups (range neutral: 1075–1899 ms, range negative: 1758–1913 ms). Mean durations were 1628 ms and 1842 ms for neutral and negative sounds, respectively (difference marginally significant, $\Delta = 214$, $t(16) = 1.97$, $p = 0.066$).

To create an associative link between sound valence and square color, the green and the blue square preceded neutral and negative sounds, respectively. Each trial started with the presentation of one of the two squares for 500 ms. Next, a sound was played over a pair of headphones, after which the subjects were presented a continuous scale (from 0 for 'neutral' to 10 for 'unpleasant') on which they rated the emotional valence of the sound via mouse click. In total, there were 36 trials, each square–sound combination was presented and rated twice.

The experiment proper started in the fourth block, in which the temporal generalization task was combined with the presentation of the colored squares and sounds in between S1 and S2. On each trial, one of the two colored squares was presented for 900, 1100 or 1300 ms. These jittered durations were chosen to allow for the buildup of expectancy and to prevent that the presentation duration influences later temporal performance. Additionally, jittered durations increased uncertainty as sounds might occur at 900, 1100 or 1300 ms after square onset, or not at all. On half the trials, no sound was presented (the no-sound condition), on the remaining trials an associatively linked emotional sound (with-sound condition) was played to evoke an emotional response. The no-sound condition was included to leave participants uninformed about whether or not they will hear a sound, to prevent habituation, and to increase the strength of the emotion manipulation (Sarinopoulos et al., 2010).

A schematic overview of the trial set-up is presented in Fig. 1. Each trial started with a screen presenting the word 'BLINK' for 1500 ms instructing the subjects to blink their eyes now rather than during the remainder of the trial. This screen was followed by a fixation cross (500 ms), a blank screen (1000 ms), S1 (1200 ms), a second blank screen (500 ms), the colored square representing the cue (blue/green, for 900, 1100 or 1300 ms), followed by the combined presentation of the square and the sound in half of the trials, or followed by the presentation of the square for a randomly selected duration equal to that of one of the eighteen sounds. After this, a blank screen was presented for 500 ms, followed by the presentation of S2 (either 1040, 1120, 1280, or 1360 ms) and eventually a response screen with a question mark indicating that the response should be made by pressing the 'z' or 'm' key. A new trial started after a response was made.

In total there were 216 trials: Each of the cells in the 2×2 design consisting of cue (neutral/negative) and sound presence conditions was presented 54 times, allowing for three presentations of each of the 18 sounds in the with-sound condition. The S2 durations were pseudo-randomly distributed, resulting in 52 to 56 presentations of each S2 duration per participant. After 108 trials, a short break was introduced in which subjects were instructed to press the space-bar when they were ready to continue. The experiment lasted approximately fifty minutes and took place in the presence of the experimenter in a room where subjects were tested either individually or in pairs.

2.1.3. Method of Analysis

Data from the conditioning/sound-rating block and the experimental block were analyzed. Valence ratings collected in the conditioning/sound-rating block were evaluated by comparing the mean ratings of the sounds with a *t*-test. The temporal generalization data collected in the experimental block were analyzed using logistic mixed-effect models. The dependent variable in these models was whether the participant responded 'long' (1) or 'short' (0). Because of this coding, the estimated betas reflect the change in the proportion of 'long' responses, expressed on a logit-scale. Compared to the traditional approach of estimating parameters on a subject-by-subject basis which are then entered into an ANOVA, logistic mixed-effect models provide a more powerful analysis method. This method allows for, among other advantages, the straightforward inclusion of continuous covariates, analyzing designs with unequal number of observations per cell, for assessing the goodness of fit of a model, and to compare the goodness of fit with alternative models. We have utilized this method in earlier work (Van Rijn, 2014), and a more extensive description of the method and its application to psychophysical data can be found in a recent methods paper (Moscatelli et al., 2012).

We entered predictors representing whether the sound was present, whether a negative or neutral cue was used, and the interaction of these predictors as fixed factors in the mixed-effect model. We also entered the duration of S2 as a fixed effect, but used model comparisons to assess whether interactions between S2 duration and the other fixed effects were warranted. Similarly, we assessed whether the inclusion of trial number (i.e., 'time on task') and cue duration was warranted using model comparisons. For the fixed factors representing sound presence and valence, deviation or effects coding was used (sound: 0.5; no-sound: –0.5; neutral: –0.5; negative: 0.5), trial number was rescaled to a range from –0.5 to 0.5, the duration of the cue was expressed as the deviation in seconds from 1.1 s (i.e., –0.2, 0, 0.2), and the duration of S2 was encoded as deviation in seconds from 1.2 s (i.e., –0.16, –0.08, 0.08, 0.16). As random effects, we entered a factor representing participant to account for (intercept) effects associated with specific participants. As not all trials involved the presentation of a sound, the sounds were not entered as a random factor.

2.2. Results

The ratings obtained in the conditioning/sound-rating block indicated an appropriate operationalization. The neutral sounds were rated between 1.76 and 3.45 ($M = 2.34$, $SD = 1.39$; see Table 1) and the negative sounds between 6.05 and 7.88

Table 1.
Brief descriptions of the negative and neutral sounds used in Experiment 1 (and 2). Numbers in parentheses indicate the rating given to these sounds in Experiment 1. One of the Phone ringing sounds was replaced by a 'bell' sound (rated with 2.3) in Experiment 2. See text for further explanation.

Negative sounds	Neutral sounds
Chalk screeching on blackboard (7.4)	Boing, spring-like sound (2.1)
Dental drill (7.1)	Doorbell (ding dong) (2.1)
Fork scraping in bowl (7.2)	Clarinet playing (1.8)
Group of people screaming (7.9)	Horse whinny (2.4)
Squeaky screw driver (7.6)	Birds singing (2.4)
Squeaky wheel (6.1)	Phone ringing (3.0)
Scratching materials (7.6)	Babbling and running sounds of a baby (2.0)
Screeching noise of a microphone (7.0)	Samba drums and background singing (1.9)
Shrieks of a knife on a glass bottle (7.2)	Phone ringing (3.4)

($M = 7.23$, SD = 2.06). This difference was statistically significant indicating that the negative sounds were indeed perceived as more negative than the neutral sounds ($\Delta = 3.89$, $t(19) = 17.32$, $p < 0.001$).

Data of the temporal generalization study are depicted in Fig. 2, in which the four lines depict the four cells of the two (valence) by two (sound presence) design, plotted as a function of the four S2 durations. To analyze these data, we started with the simplest logistic mixed model containing the factors sound presence, valence, their interaction, and S2 duration. When we compared this model with a more complex model in which interactions between S2 duration and the other factors were entered, the simpler model prevailed ($\chi^2 = 0.852$; df = 3; $p = 0.837$). To ensure that the jittered duration associated with the cue presentation did not influence the results, we also compared a model in which the cue duration was entered as a fixed factor, but, again, the simpler model was preferred ($\chi^2 = 0.192$; df = 1; $p = 0.661$). Similarly, including trial number did not improve the fit of the model ($\chi^2 = 2.24$; df = 1; $p = 0.135$). Although the non-significant χ^2 test indicates that the inclusion of trial number is not warranted, it is relevant to note that the associated estimate is negative, which is in the same direction as the effects of valence and the interaction between valence and sound presence. In other words, habituation is unlikely to have affected those effects in qualitative terms.

The resulting model, which is the base model we started with, contains significant effects for all factors. An intercept of –0.22 ($z = -2.32$, $p = 0.020$) indicates that, at the average duration of S2, the proportion of 'long' responses significantly deviated from chance (estimated P(Long): 0.45). In other words, S2 duration was

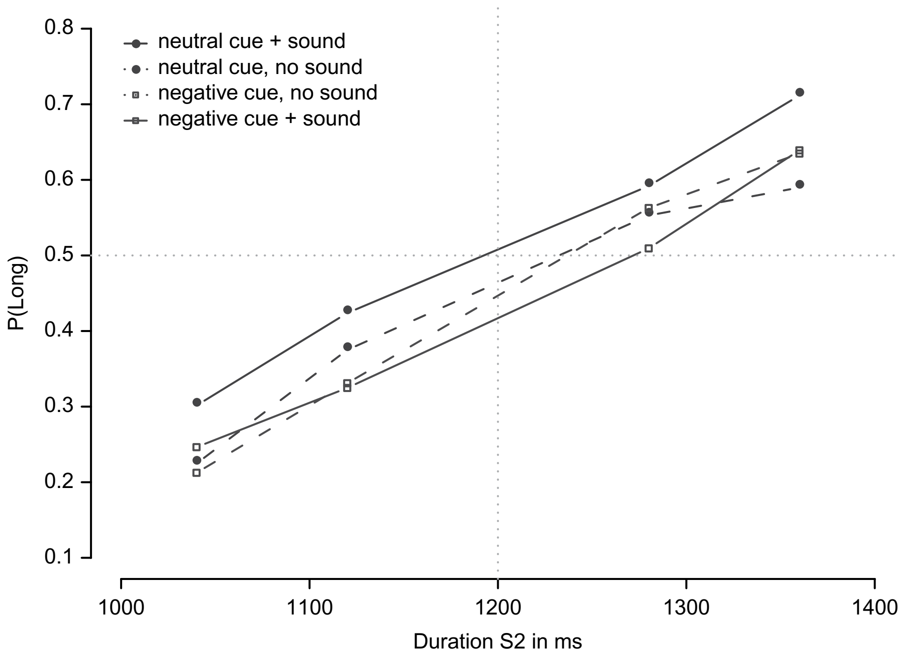

Figure 2. Proportion of 'long' responses for the four S2 durations for the two emotional valence and two sound presence conditions in Experiment 1. This figure is published in color in the online version.

underestimated. Due to the deviation coding, the interpretation of the other parameters is less straightforward. The significant main effect of valence ($\beta = -0.16$; $z = -2.46$, $p = 0.014$) indicates that, when the cue is negative, people are less likely to respond 'long'. The main effect of sound presence ($\beta = 0.15$; $z = -2.32$, $p = 0.020$) indicates that omitting the sound increases the proportion of 'long' responses. Importantly, these main effects are modulated by an interaction between sound presence and valence ($\beta = -0.39$; $z = -2.97$, $p = 0.003$). The proportion of 'long' responses for the neutral/no-sound condition and for the negative/sound condition is lower than the proportion of 'long' responses for the other two conditions. The duration of S2 had, obviously, a large effect on the proportion 'long' responses ($\beta = 5.44$; $z = 20.4$, $p < 0.001$), indicating that with longer durations the proportion of 'long' responses increased. To ensure that these effects were not driven by differences in sound durations, we compared the simplest model with a model that additionally contained a predictor encoding for the duration of the sound (deviation in seconds from the mean duration). Again, the simpler model was preferred, indicating that the added complexity was not warranted ($\chi^2 = 0.024$; df $= 1$; $p = 0.135$). Inspecting the other estimates of the more complex model also showed that all estimates where highly similar to the ones in the simpler model, suggesting that even if the more complex model were warranted, it would have led to similar conclusions. To assess whether any effects of valence can be observed when no sound was presented, we conducted a separate analysis on the no-sound trials. As might be expected on the basis of Fig. 2, the two square colors alone did not significantly influence the proportion of 'long' responses ($\beta = 0.034$; $z = 0.363$, $p = 0.717$).

2.3. Discussion

The results are in line with Lui et al.'s (2011) work with respect to the hypothesized effects in the sound condition: when a negative sound is presented, the duration is perceived as shorter resulting in fewer 'long' responses. This can be explained by a modulation of attention: a negative sound captures more attention than a neutral sound, which comes at a cost to attention allocated to time perception, hence pulses are missed and the S2-durations are perceived as shorter. Although the S2 durations were selected with the intention to observe a large number of correct responses for the more extreme durations, we failed to observe the typical sigmoid pattern. We, therefore, conducted a second study in which a shorter and a longer S2 duration were added and in which the sound durations were better controlled. Additionally, one of the two phone-ringing sounds was replaced by a bell sound, and green and red cues were used instead of green and blue cues to ensure a larger color contrast and a more naturalistic mapping.

3. Experiment 2

3.1. Methods

3.1.1. Participants

A total of 23 naïve subjects (mean age = 22.9; SD = 2.63; range: 19–30, 11 male) participated. All subjects were enrolled at the University of Groningen and received 10 Euros per hour in exchange for participation. All participants reported to have normal or corrected-to-normal sight and normal hearing. Ethics approval was obtained from the Psychology Ethics Committee of the University of Groningen.

3.1.2. Materials

With a few exceptions, the materials used in Experiment 2 were similar to those used in Experiment 1. First, as two phone ringing sounds were used in Experiment 1, one was replaced by the sound of a bell. Second, the sounds were edited to ensure more similar durations for the two conditions. Removing or adding parts to the signal resulted in a time range of 1738 to 1902 ms and 1758 to 1913 ms for the neutral and negative sounds, respectively. These differences in duration were non-significant ($M_{\text{Neutral}} = 1838.7$ and $M_{\text{Negative}} = 1842.6$; $\Delta = 3.9$, $t(16) = 0.138$, $p = 0.89$). Third, green and red squares were used to increase color contrast. The red cue indicated the negative valence condition, the green cue the neutral valence condition. Fourth, as the data collected in Experiment 1 suggested that responses to the shortest and longest S2 durations were far from asymptotic, we added two extreme durations (960 and 1440 ms).

3.1.3. Procedure

As her/his EEG was collected during this experiment, each participant was tested individually in a shielded room. However, due to technical problems the signal-to-noise ratio was too low to warrant the reporting of these data.

The practice blocks and the conditioning/sound-rating blocks were identical to those in Experiment 1, with the exception of two more extreme durations added to the second practice block. This increased the number of trials in the second practice block as all durations were again repeated ten times, in random order.

The experimental block consisting of the temporal generalization task with cues and sounds was identical to Experiment 1, except for the two additional S2 durations and the new color–cue mappings. In total there were 180 trials: 90 trials for the with- and 90 for the no-sound condition, half of which were negative and half of which were neutral. Each sound was presented 5 times. The S2 durations were pseudo-randomly distributed, resulting in 28 to 32 presentations of each S2 duration per participant. After 90 trials, participants could take a short, subject-paced break. The whole experiment took about 45 minutes.

3.1.4. Method of Analysis

The method of analysis was equivalent to that of Experiment 1.

3.2. Results

Again, the sound ratings indicated a proper operationalization. The neutral sounds were rated from 1.06 to 3.59 ($M = 2.03$, SD $= 1.96$) and the negative sounds from 5.56 to 8.22 ($M = 7.37$, SD $= 2.02$), resulting in a significant difference between the two sound conditions ($\Delta = 5.34$, $t(22) = 18.07$, $p < 0.001$).

The main data of the temporal generalization study are depicted in Fig. 3. As can be seen from this picture, the results clearly deviate from those obtained for

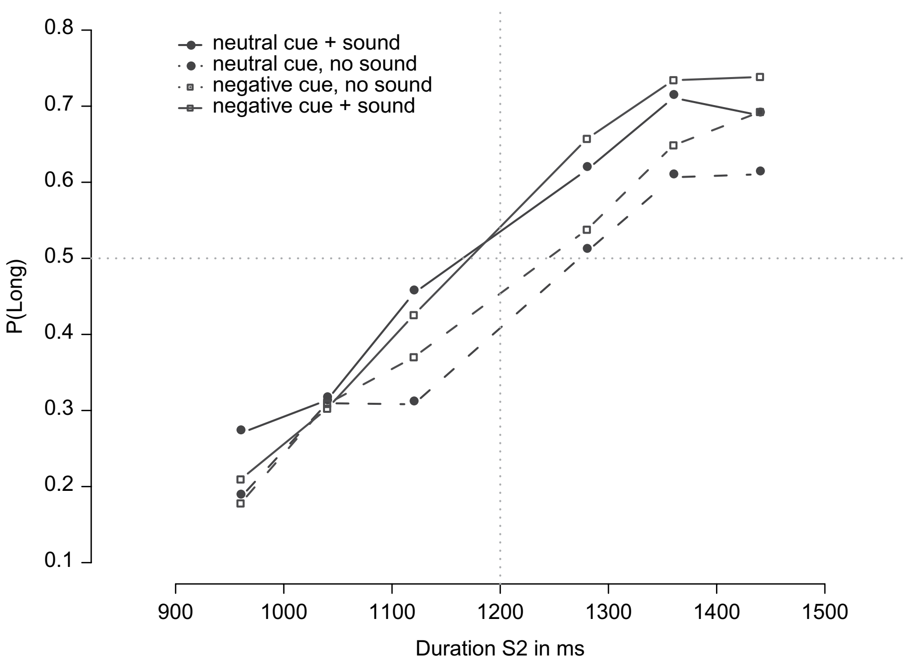

Figure 3. Proportion of 'long' responses for the six S2 durations for the two emotional valence and two sound presence conditions in Experiment 2. This figure is published in color in the online version.

Experiment 1 as there is no clear difference between the neutral and negative sound conditions.

To quantify these results, we again started with the simplest logistic mixed model containing the factors sound presence, valence, their interaction, and S2 duration. As for Experiment 1, we tested a number of more complex models. Both the more complex model that included S2 duration interacting with sound presence and valence ($\chi^2 = 5.284$; df = 3; $p = 0.152$) and the more complex model that included the cue duration ($\chi^2 = 1.315$; df = 1; $p = 0.252$) were non-preferred over the simpler model. However, the more complex model that also included trial number was preferred over the simpler model ($\chi^2 = 9.015$; df = 1; $p = 0.003$). Extending this model with sound duration was not warranted ($\chi^2 = 0.026$; df = 1; $p = 0.872$).

The preferred model consisted of a non-significant intercept ($\beta = -0.13$; $z = -1.19$, $p = 0.232$) and a highly significant effect of S2 duration ($\beta = 4.77$; $z = 22.7$, $p < 0.001$) indicating that longer S2 durations were associated with a higher proportion of 'long' responses. A significant effect of sound presence ($\beta = 0.350$; $z = 5.08$, $p < 0.001$) indicated that trials with sound were associated with higher proportions of 'long' responses than trials without sound. The effect of valence ($\beta = -0.120$; $z = 1.74$, $p = 0.082$), and the interaction between sound presence and valence ($\beta = -0.219$; $z = -1.59$, $p < 0.111$) were non-significant. The trial effect was significant ($\beta = -0.35$; $z = -3.00$, $p = 0.003$), indicating that participants started to respond short more often as the experiment progressed.

Of these results, the lack of a significant main effect of valence is most important and indicates that Experiment 2 failed to replicate Experiment 1. At the same time, the estimated beta is negative for both Experiments 1 and 2, and the effect in Experiment 2 could be interpreted as 'borderline significant'. However, Fig. 3 indicates that this interpretation is not supported by the data, as no effect can be observed in the sound condition (the solid lines). Moreover, an effect of emotional valence should be stronger in the sound conditions than in the no-sound conditions, another hypothesis which is clearly not supported by the data. Therefore, the results of Experiment 2 are at odds with the assumption that emotional auditory stimuli affect the perception of time.

4. General Discussion

Do emotional stimuli affect the subjective experience of time? The results of Experiment 1 support an affirmative answer to this question: durations in the emotional sound condition were perceived as shorter than durations in the neutral sound condition. These results are in line with the study of Lui et al. (2011), and generalize their findings from the visual domain to the auditory domain. Moreover, they are most straightforwardly explained by an attentional mechanism: a negative sound captures more attention compared to a neutral sound, which comes at the cost of attention allocated to time perception, hence pulses are missed and the S2 durations are perceived as shorter. In the no-sound condition, that is when only the cue was presented that could be used to predict the valence of the sound, no effect was observed. As we cannot quantify how well the association between cue and valence was learned, the absence of an effect might simply be due to a too weak association between the visual cue and the sound. In other words, seeing the colored square may not have evoked an emotional response. However, effects of conditioning might also be negated by color-inherent responses as in the design of Experiment 1 (and 2) the colors of the cues were not counterbalanced. Thus, if a cue signaling a negative sound caused a stretching of time, the negative sound effect would have been canceled out. As these effects cannot be quantified with the current setup, no firm conclusions should be drawn based on the absence of an effect in the no-sound condition.

To sum up, the present results can be seen as an auditory analogue of earlier work, as they support the view that hearing a negative sound results in an underestimation of time immediately after the sound was heard. In other words, perceived time is slowed down in situations preceded by an unpleasant experience (see, for example, Gan et al., 2009; Lui et al., 2011; Noulhiane et al., 2007). Although this attentional account fits the present results, it is possible that in other temporal tasks the emotional modulation is driven by changes in arousal. Moreover, as we have not explicitly measured biophysiological markers of arousal, it could be that some of the observed results are driven by an interplay between arousal and attentional processes (see also this issue Droit-Volet et al., 2016; Eberhardt et al., 2016, Schirmer et al., 2016).

Irrespective of the underlying mechanisms, an important observation is that Experiment 2 failed to replicate the findings of Experiment 1. Moreover, post-hoc explorations have failed to unravel why Experiment 2 failed to show effects: there were no participants with clearly outlying data, nor did certain sounds illicit qualitatively different responses (a conclusion also supported by the similar results for the sound ratings in Experiments 1 and 2). In Experiment 2, as in Experiment 1, the presentation of a sound between the presentation of the standard and the comparison intervals affected the subjective perception of time, an effect that can be explained in terms of an arousal-based mechanism.

A potential explanation for the lack of valence effects is that participants in Experiment 2 might have been more motivated, as EEG data were collected in addition to behavioral data. If higher levels of motivation resulted in a more focused processing of temporal information, the emotional modulation might not have been strong enough to distort the accumulation of time (Droit-Volet et al., 2016). Another potential explanation, also related to the EEG setup of Experiment 2, is that A. Schirmer (personal communication, Sept. 26, 2015) indicated that emotional effects might be more difficult to observe when participants are tested in a separate room without other participants or the experimenter present. Yet another explanation could be that in this experiment more trials were run than in earlier studies assessing the emotional effects on timing. For example, in Lui et al. (2009) AQ1 participants were presented only 64 trials. However, the lack of an effect of trial number in Experiment 1, and the relatively minor influence of the inclusion of trial number on the other parameters in Experiment 2 make this explanation less likely. A final alternative explanation might relate to the shorter time between trials AQ1 in our experiments, as in the study by Lui et al. (2009) trials were separated by about nine seconds. Although this could, of course, be a cause for the lack of effect in Experiment 2, the observation of a valence effect in Experiment 1, which has a similar setup as Experiment 2, makes this explanation questionable.

As Experiment 1 seems to be most in line with earlier (e.g., Gan et al., 2009; Lui et al., 2011; Noulhiane et al., 2007) and recent (Lake et al., 2016) results, both with similar and slightly different experimental setups (e.g., Gan et al., 2009; Lui et al., 2011; Noulhiane et al., 2007), we are tempted to place more trust in the results of Experiment 1. At the same time, Experiment 2 is an interesting wake-up call for researchers studying the emotional modulation of interval timing: rerunning a study with participants from a similar participant pool and a highly similar experimental setup made some presumably stable effects disappear. In addition, to assess how emotional stimuli influence interval timing, an important line of research should be to establish how robust these findings are by running a number of large-scale, preregistered studies (Open Science Collaboration, 2015), and to address whether there are certain interindividual differences that might explain the susceptibility to emotional influences (Schirmer et al., 2016). In addition, the differential effects of emotional stimuli suggest that running a series of preregistered, adversarial collaborations (Matzke et al., 2015) might be necessary to advance this line of research on interval timing.

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