Perceptual complexity, rather than valence or arousal accounts for distracter-induced overproductions of temporal durations ☆

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ABSTRACT

For humans and other species, the ability to estimate the physical passage of time is of fundamental importance for perceptual, cognitive or motor functions. Despite this importance, any subjective estimation of temporal durations not only depends on the temporal dynamics of the to-be-timed stimulus or event, but also can be distorted by non-temporal perceptual, cognitive, and emotional effects. This study aimed to further explore critical stimulus characteristics modulating distracter-induced distortions in human time-reproduction. To this end, we investigated whether subjectively rated distracter dimensions of arousal and valence (related to levels of emotionality), or rather stimulus complexity, as a confounder, produce distortions in participants' reproduction of a previously trained target interval. Accuracy and precision of time-reproduction have been measured in distracter-trials, and compared to timing performance in baseline-trials without any distraction. Results showed temporal overproductions in a magnitude of less than distracter duration only for complex distracters. Most importantly, arousal level and valence of distracters were not accountable for temporal distortions. Within an internal clock framework, our pattern of results can best be interpreted in the context of attention-, rather than arousal-based mechanisms of timing.

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1. Introduction

For humans and other species, the ability to estimate the physical passage of time is of fundamental importance for perceptual, cognitive or motor functions (Buhusi & Meck, 2005). Despite this importance, subjective timing not only depends on the temporal dynamics of the to-be-timed stimulus or event, but is susceptible to cognitive demands of the timing task (Block, 1992; McClain, 1983), and to a number of non-temporal stimulus characteristics including perceptual (Terao, Watanabe, Yagi, & Nishida, 2008; van Wassenhove, Buonomano, Shimojo, & Shams, 2008; Wittmann, van Wassenhove, Craig, & Paulus, 2010; Xuan, Zhang, He, & Chen, 2007), attentional (Fortin, 2003; Fortin & Massé, 2000; Fortin, Bédard, & Champagne, 2005; Macar, 1996; Tremblay & Fortin, 2003), and emotional factors (Angrilli, Cherubini, Pavese, & Manfredini, 1997; Block, 1992; Droit-Volet, Brunot, & Niedenthal, 2004; Effron, Niedenthal, Gil, & Droit-Volet, 2006; Gil, Niedenthal, & Droit-Volet, 2007; Noulhiane, Mella, Samson, Ragot, & Pouthas, 2007).

In humans, rodents, and birds temporal distortions of physical durations could be sufficiently explained by internal clock models as they were derived from Scalar Expectancy Theory (Church, 1978; Gibbon, 1977; Gibbon & Church, 1984; Gibbon, Church, & Meck, 1984; Treisman, 1963; Wearden & McShane, 1988). In its simplest form, an internal clock model proposes a pacemaker, an attention-dependent clock-switch, and an accumulator. The pacemaker generates discrete pulses (or units of elapsed time) at a fixed frequency. The clock-switch closes at the beginning of each time-estimation process, thereby causing a number of pacemaker pulses to enter the accumulator which counts these pulses until the switch opens again, thus terminating the timing process. The final accumulator-count can be transferred to reference memory, where it is stored as a reference count value (or criterion count). When reproduction of memorized target durations is required, the current number of pulses in the accumulator is compared to the stored reference count value, until a match of both values terminates participants' time-reproduction (Church, 1978; Gibbon, 1977; Gibbon & Church, 1984; Gibbon et al., 1984; Treisman, 1963; Wearden & McShane, 1988).

An important implication of the standard internal clock model is the assumed dependence of timing-accuracy on the number of

pacemaker pulses accumulating within a given time span: the more pulses accumulate the longer the perceived duration. In this perspective, any misperception in time results from a change in the number of accumulated pulses. Two mechanisms, one of physiological arousal, and one of time- or resource-sharing can be considered to produce such a change. Firstly, increases in physiological arousal might increase the pulse rate of the internal clock's pacemaker, thus producing overestimations of physical durations (Burle & Casini, 2001; Wittmann & Paulus, 2008). Similarly, decreases in physiological arousal might decrease the internal clock's pulse rate, thereby producing temporal underestimations (Buhusi & Meck, 2002). Alternatively, an attention-dependent mechanism of time- or resource-sharing can account for temporal over- or underestimations (Fortin, 2003; Fortin & Massé, 2000; Rousseau, Picard, & Pitre, 1984). Different amounts of time- or resource-sharing between the timing process and the simultaneous processing of to-be-timed stimuli, gaps (i.e., stimulus-free interruptions), or distracters (e.g., task-irrelevant visual or auditory stimuli) might modify the 'flickering'-rate of the attention-dependent clock-switch (i.e., the rate of oscillation between an open and a closed state; Leyeune, 1998, 2000). In this perspective, overestimations of physical durations will occur in response to an increased oscillation-frequency holding the clock-switch much longer in a closed state, thereby allowing more pulses to enter the accumulator. Contrary, underestimations of physical durations will occur in response to a decreased oscillation-frequency holding the clock-switch much longer in an open state, thereby producing a loss of accumulated pulses.

There is yet no conclusive answer as to what kind of mechanism that of arousal or of time- or resource-sharing, primarily accounts for temporal distortions of physical durations. Several studies in human time perception revealed valence- and arousal-dependent overestimations of physical durations (e.g., Angrilli et al., 1997; Block, 1992; Droit-Volet et al., 2004; Effron et al., 2006; Gil et al., 2007; Noulhiane et al., 2007). However, these studies used emotional stimuli (e.g., faces, non-facial pictures, or sounds) as primary stimuli, and required participants to estimate the duration of the same arousing stimuli that presumably instigated arousal. Thus, temporal and non-temporal factors were intermingled, and the observed arousal- and valence-dependent effects on subjective time-estimation might be rather explained by confounding variables, e.g., the complexity, semantics, or saliency of the to-be-timed stimulus (e.g., Buhusi, 2012; Buhusi, Sasaki, & Meck, 2002; van Wassenhove et al., 2008; Wittmann et al., 2010).

Time-reproduction studies with gaps or distracters allow for a clear differentiation of temporal and non-temporal factors. Such studies revealed underestimations (or overproductions) of critical target durations, and regularly attributed these effects to an attention-dependent mechanism of interval timing (Bherer, Desjardins, & Fortin, 2007; Buhusi, 2012; Buhusi & Meck, 2000, 2006a,b; Casini & Macar, 1997; Champagne & Fortin, 2008; Fortin & Massé, 2000; Fortin et al., 2005; Olton, Wenk, Church, & Meck, 1988; Roberts, 1981; Tremblay & Fortin, 2003). However, most time-reproduction studies were conducted in rodents and birds, and employed only gaps or perceptually simple and less arousing non-emotional distracters (e.g., single light and tone stimuli, or simple geometric figures). Thus, in these studies possible contributions of distracter dimensions of arousal, valence, and stimulus complexity have not been tested.

The present study aimed to further explore, whether subjectively rated distracter dimensions of arousal and valence (related to levels of emotionality), or rather stimulus complexity, as a confounder, can explain distortions in participants' reproduction of a previously trained target interval. To this end, we employed a psychophysical paradigm that I) allowed disentangling temporal and non-temporal variables, II) enabled sufficient control of the most important distracter dimensions, and III) ensured a comparable task difficulty across experimental conditions. Participants were firstly trained to accurately estimate a neutral (i.e., 'empty') time interval, and were than required to

reproduce the trained target duration that was 'interrupted' by a distracting stimulus, thus creating a situation with a primary (carrier) stimulus that has to be attended to (i.e., the to-be-timed stimulus) and a secondary distracter stimulus that was varied according to dimensions of arousal, valence, and stimulus complexity. Thus, the chosen paradigm is different from previous studies in human time perception (e.g., Angrilli et al., 1997; Block, 1992; Droit-Volet et al., 2004; Effron et al., 2006; Gil et al., 2007; Noulhiane et al., 2007) where emotional stimuli were used as primary (carrier) stimuli. For practical reasons (e.g., total duration of the experimental session, avoidance of presentation of sexually related stimuli) only three distracter-subsets were tested containing combinations of A) low-arousing neutral and perceptually simple stimuli, B) medium-arousing neutral and perceptually complex stimuli, and C) high-arousing unpleasant and perceptually complex stimuli. The generation of these subsets allowed for measurements of the extent to which timing processes could be affected by each of the self-assessed distracter dimensions.

We expected misperceptions of the trained target duration to occur in trials with presentations of medium- and high-arousing neutral and unpleasant distracters, when stimulus complexity rather than arousal or valence accounts for distracter-induced temporal distortions. In the case that distracter valence is accountable for temporal distortions, misperceptions were expected to occur only in trials with presentation of high-arousing and unpleasant distracters. Finally, temporal mis-perceptions occurring after presentations of low-, medium-, and high-arousing stimuli were considered to be indicative of arousal-dependent temporal distortions.

2. Experiment

2.1. Method

2.1.1. Participants

Twenty-one university-educated young adults (12 women and 9 men) were recruited for participation in this study. Their age ranged from 20 to 38 years ($M = 25.5$ years, $S.E. = .99$). All participants were healthy, had normal or corrected-to-normal vision, and were without any history of neurological or psychiatric disease or head injury. They were novices in psychophysical tasks, were paid for participation, and were naive with regard to the purpose of the study. Prior to the experiment, informed written consent was obtained. This study had the approval of the Ethics Committee of the German Society for Psychology, and was conducted in accordance with the Declaration of Helsinki.

2.1.2. Apparatus and stimuli

The experiment was conducted in a quiet room with an illumination level approximately matching the luminance of the screen (35 cd/m^2). Participants were seated in front of the monitor and used a chin rest to ensure stable binocular fixation on the screen. Viewing distance was 57 cm. Two loudspeakers (Logitech X-120, 10 W) were placed underneath the monitor and provided feedback tones (60 dB SPL, 587 Hz, 50 ms duration). Visual stimuli comprised a fixation stimulus (small white square, 10×10 pixels), a marker stimulus (black square, 200×200 pixels, 1 s duration) and 3 subsets of distracter stimuli (400×300 pixels, 2 s duration), which were displayed on a LaCie electron22blue IV 20″ CRT monitor (resolution: 1600×1200 pixels; refresh rate: 75 Hz). The background color of the monitor was set to gray. During the experiment, timing and stimulus presentation were controlled by custom-made laboratory software running on an Apple Power Mac Dual G4 (1250 MHz; system software: Mac OS 9.2). Participants responded by continuously pressing, or releasing the 'L'-key on a standard numerical keyboard, and were instructed to respond with the middle or index finger of their dominant hand.

Distracter stimuli were chosen from the International Affective Picture System (IAPS; Lang, Bradley, & Cuthbert, 2008), and were

supplemented by two in-house pictures. The IAPS-database was developed in order to provide standardized material for the study of emotion and attention. Most importantly, ratings of affective valence and arousal are provided for a large set of photographs covering a wide range of semantic categories (Lang et al., 2008). To confirm the reliability of published IAPS-ratings (obtained from U.S. students), German students ($N = 40$), not serving as participants in the time-reproduction study, pre-rated IAPS-pictures (supplemented by two in-house pictures) that were characterized by neutral or unpleasant valence, as well as low, medium or high arousal. These pictures were rated on separate 9-point rating scales according to their subjective valence (unpleasant to pleasant), level of arousal (calm to excited), and perceptual complexity (simple to complex). Perceptual complexity (not part of the IAPS-ratings) was defined as the amount of detail or intricacy of lines in the picture (Cycowicz, Friedman, Rothstein, & Snodgrass, 1997; Snodgrass & Vanderwart, 1980). In the beginning of the rating procedure, three sample stimuli were shown as practice stimuli to allow German participants to anchor their scales. Only when pre-ratings of arousal and valence were not significantly different ($p > .05$) from corresponding IAPS-ratings (as they were reported in the IAPS technical manual; Lang et al., 2008) pictures were assigned to one of three different distracter-subsets. These subsets were characterized by I) low arousal, neutral valence, and low perceptual complexity (*neutral/simple distracters*; a white rectangle), II) medium-arousal, neutral valence, and high perceptual complexity (*neutral/complex distracters*; IAPS Slide No. 2383, 2435, 2575, 2840, 5535, 5720, 7500, 7503, 7550, and one in-house picture), or III) high arousal, unpleasant valence, and high perceptual complexity (*unpleasant/complex distracters*; IAPS Slide No. 2900, 3180, 3181, 3301, 3350, 9041, 9300, 9440, 9471, 9810).

2.1.3. Design and procedure

Previous timing studies in rodents and birds successfully investigated attention-dependent effects of distraction using a time-reproduction paradigm with gaps or distracters (Buhusi, 2012; Buhusi & Meck, 2000, 2006a,b; Olton et al., 1988; Roberts, 1981). Similarly to Fortin and Massé (2000), we adapted a modified version of this paradigm to the peculiarities of psychophysical testing on human subjects. Our experiment contained an initial training ($N = 80$ trials), and a subsequent experimental session ($N = 160$ trials). Before each trial, an initial fixation stimulus prompted participants to initiate the trial by pressing and holding the response key. Participants were required to release the key immediately after the occurrence of a marker stimulus (during training), or when they felt that the critical target interval had passed by (during the experimental session). Before training, participants were instructed to memorize the critical target interval comprising the time interval between pressing and releasing the response key. During the experimental session, participants had to continue their time-reproduction in the face of a distracting stimulus (i.e., they continued pressing the response key), and to reproduce the previously trained target interval, so that the time between pressing and releasing the response key, not including the duration of the distracter, approximately corresponded to the trained target duration. Most importantly, participants were not allowed to use any form of explicit or implicit counting strategies (e.g., rhythmic head movements, foot-, or finger-tapping), and were instructed not to count the length of distracters as part of the to-be-reproduced duration. A variable inter-trial interval (ITI) between 3 and 4 s was introduced to avoid implicit evaluation of fixed delays. After the ITI, the fixation stimulus re-appeared prompting participants to initiate the next trial (i.e., participants initiated each trial at their own pace).

2.1.3.1. Training.
In the beginning of the experiment, participants were trained to mentally represent a fixed target duration of 8 s. Importantly, all participants were unaware of the explicit time period they were trained to. The whole training contained a total of $N = 80$ trials, and

was divided into one block of $N = 40$ marker-trials, and a subsequent block of $N = 40$ feedback-trials. Before each training-trial, a fixation stimulus was presented centrally on the gray screen prompting participants to initiate the trial by pressing and holding the response key.

The first block of $N = 40$ trials contained marker-trials. After the initiation of these trials, the gray screen was presented for a total duration of 8 s. Thereafter, a central marker stimulus (black square) appeared for a total duration of 1 s, before the screen switched to gray again. Participants were required to release the response key immediately after the offset of the marker stimulus. An acoustic feedback tone was provided when participants released the key within 3 s after the offset of the marker stimulus. No feedback was provided for early and late responses. In the case of no response, marker-trials were terminated 3 s after the offset of the marker.

The first block of marker-trials was subsequently followed by a second block of $N = 40$ feedback-trials without any marker presentation. In these trials, the screen stayed gray for the total duration of the trial. Thus, participants had to reproduce the memorized criterion-time in the absence of any marker presentation, and were required to release the response key when they felt that the critical target interval had passed by. Acoustic feedback was provided for responses given within a response-window between 4 and 12 s after the initiation of the trial (i.e., 4 s before and after attainment of the critical target duration). In the case of no response, feedback-trials were terminated after a maximum trial duration of 20 s. At the end of the training, participants were asked if they were able to successfully memorize the critical target duration. Afterwards, they paused for 2 to 3 min before they continued with the experimental session.

2.1.3.2. Experimental session.
The experimental session served to test for the accuracy and precision of time-reproduction of the memorized target duration (8 s) in the presence (distracter-trials) and absence of visual distracters (baseline-trials). Importantly, no feedback about timing performance was provided throughout the experimental session. Baseline-trials were characterized by presentation of a gray screen that continued for the total duration of the trial. Participants had to reproduce the memorized criterion time, and were required to release the response key when they felt that the critical target interval had passed by. Distracter-trials contained an initial time period of 4 s of gray screen, followed by a 2 s distracter presentation, and a subsequent period of gray screen again. Participants were instructed to continue their time-reproduction in the face of a distracting stimulus, and to reproduce the previously trained target interval, so that the time between pressing and releasing the response key, not including the duration of the distracter, approximately corresponded to the trained target duration. In the case of no response, distracter- and baseline-trials were terminated after a maximum trial duration of 20 s. Previous studies revealed an effect of distracter location on human time-reproduction with small temporal distortions induced by distracting signals presented in the beginning, and relatively higher distortions induced by distracting signals presented near the end of the to-be-timed interval (Fortin & Massé, 2000; Fortin et al., 2005; Tremblay & Fortin, 2003). This effect was suggested to depend on the expectancy of the distracting signal producing different amounts of time- or resource-sharing (Fortin, 2003; Fortin & Massé, 2000). To ensure a comparable amount of expectancy-dependent time- or resource-sharing, we presented all distracters in the middle of the to-be-timed interval (i.e., always 4 s after the initiation of the trial), and used a fixed distracter duration of 2 s.

Our experimental session contained a total of $N = 160$ time-reproduction trials that were divided into 4 experimental blocks of $N = 40$ trials per block. Each block contained $N = 5$ baseline-trials subsequently presented in the beginning of the block, $N = 30$ distracter-trials (10 successive trials for each of the three distracter-subsets), and another $N = 5$ baseline-trials presented at the end of

each block (see Fig. 2). Within each block, the sequence of distracter-subsets, as well as the order of stimuli for each of the three subsets were randomized.

2.1.3.3. Distracter-ratings. In order to verify pre-ratings of arousal, valence, and perceptual complexity, participants post-rated all 31 distracter stimuli on separate 9-point rating scales according to their subjective valence (unpleasant to pleasant), level of arousal (calm to excited), and perceptual complexity (simple to complex). According to Cycowicz et al. (1997) and Snodgrass and Vanderwart (1980), perceptual complexity was defined as the amount of detail or intricacy of lines in the picture. Each participant was asked with the question 'How difficult is it to draw or to trace this picture — is it hard (scored 9), medium (scored 5), or easy (scored 1)?' Participants were advised to rate the complexity of the picture itself rather than the complexity of the real-life object it represented. In the beginning of the rating procedure, three sample stimuli were shown as practice stimuli to acquaint participants with the procedure, and to allow them to anchor their scales. Participants advanced from picture to picture at their own pace. At the end of the experiment, a debriefing was conducted in order to verify that all instructions had been well understood.
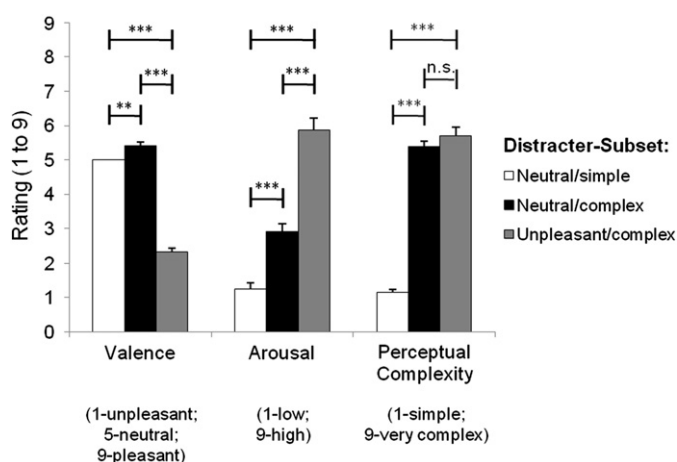
2.1.4. Data analysis

Statistical analyses consisted in repeated measures analyses of variance (ANOVAs) and Bonferroni–Holm-corrected paired *t*-tests performed using SPSS 20.0.0 (SPSS Inc., Chicago, IL, USA). Based on a Mauchly's test of sphericity, Greenhouse–Geisser-corrected *p*-values were used to verify the statistical significance ($p < .05$, two-sided) of effects. In addition, one-sample *t*-tests ($p = .05$, two-sided) and Pearson product moment correlations (r) were applied to the data.

2.2. Results

2.2.1. Rating of distracter dimensions

Fig. 1 summarizes means (*M*) and standard errors (*S.E.*) of participants' self-assessed distracter ratings of arousal, valence, and perceptual complexity. To confirm the consistency of judgments with respect to ratings obtained from a preceding pilot study, separate repeated measures ANOVAs with the within-subject factor 'distracter-subset' (neutral/simple, neutral/complex, and unpleasant/complex distracters) were calculated for subjective ratings of arousal, valence,

and perceptual complexity. Separate analyses were necessary, because scales increased linearly (1-low to 9-high) for ratings of perceptual complexity and arousal, but showed a non-linear increase (1—unpleasant; 5—neutral; 9—pleasant) for valence ratings (i.e., ratings were not completely comparable between distracter dimensions).

2.2.1.1. Arousal ratings. The statistical analysis of subjective arousal ratings (1—low; 9—high; see Fig. 1) resulted in a significant main effect of 'distracter-subset' ($F(2, 40) = 126.13$, $p < .001$). Bonferroni–Holm-corrected post-hoc paired *t*-tests confirmed a significant difference in arousal between neutral/simple and neutral/complex stimuli ($t(20) = 8.27$, $p < .001$), neutral/simple and unpleasant/complex stimuli ($t(20) = 13.35$, $p < .001$), and between neutral/complex and unpleasant/complex stimuli ($t(20) = 9.34$, $p < .001$). Thus, subjective arousal ratings systematically increased from neutral/simple ($M = 1.24$, $S.E. = .19$) to neutral/complex ($M = 2.91$, $S.E. = .23$), and unpleasant/complex visual distracters ($M = 5.88$, $S.E. = .34$).

2.2.1.2. Valence ratings. Valence ratings (1-unpleasant; 5-neutral; 9-pleasant; see Fig. 1) revealed a significant main effect of 'distracter-subset' ($F(2, 40) = 338.09$, $p < .001$). Bonferroni–Holm-corrected post-hoc paired *t*-tests revealed a significant difference between neutral/simple and neutral/complex stimuli ($t(20) = 3.46$, $p < .01$), neutral/simple and unpleasant/complex stimuli ($t(20) = 24.73$, $p < .001$), and between neutral/complex and unpleasant/complex stimuli ($t(20) = 19.50$, $p < .001$). However both, mean valence ratings for neutral/simple ($M = 5.00$, $S.E. = .00$) and for neutral/complex ($M = 5.40$, $S.E. = .11$) distracters were placed in the 'neutral' range of less than half a rating-point away from an ideal 'neutral' judgment (5—neutral), and were significantly different from judgments of negative valence for unpleasant/complex visual distracters ($M = 2.32$, $S.E. = .11$).
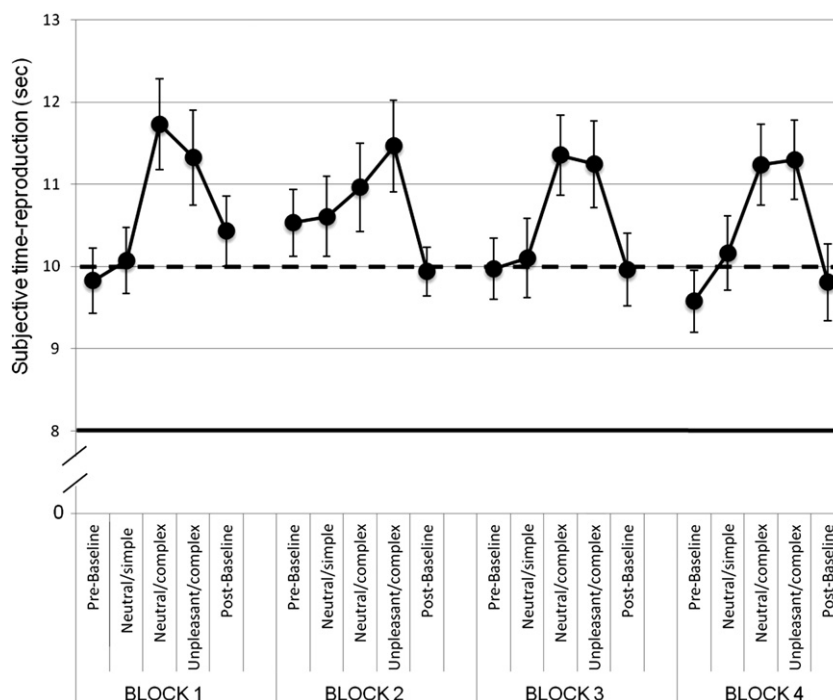
2.2.1.3. Perceptual complexity ratings. The analysis of perceptual complexity ratings (1—simple; 9—very complex) revealed a significant main effect of 'distracter-subset' ($F(2, 40) = 135.55$, $p < .001$). Bonferroni–Holm-corrected post-hoc paired *t*-tests confirmed a significant difference between neutral/simple and neutral/complex stimuli ($t(20) = 20.96$, $p < .001$), neutral/simple and unpleasant/complex stimuli ($t(20) = 19.29$, $p < .001$), and revealed no significant difference between neutral/complex and unpleasant/complex stimuli ($p > .05$). Thus, perceptual complexity ratings were comparable between neutral/complex ($M = 5.39$, $S.E. = .16$) and unpleasant/complex ($M = 5.69$, $S.E. = .26$) distracters, but were significantly different from ratings of the neutral/simple visual distracter ($M = 1.14$, $S.E. = .10$).

2.2.1.4. Interdependence of distracter dimensions. The interdependence of distracter dimensions was analyzed using a bivariate Pearson product moment correlation. As it was already mentioned before, rating scales increased linearly (1—low to 9—high) for ratings of perceptual complexity and arousal, but showed a non-linear increase (1—unpleasant; 5—neutral; 9—pleasant) for valence ratings (i.e., ratings were not completely comparable between distracter dimensions). Therefore, the interdependence of distracter dimensions was tested only for subjective ratings of perceptual complexity and arousal. The analysis revealed a strong and significant positive correlation between both distracter dimensions ($r = .725$; $p < .001$).

2.2.2. Training and time-reproduction of the trained target duration

Descriptive analysis of participants' absolute timing responses during training revealed mean responses after $M = 8.32$ s ($S.E. = .02$) in marker-trials, and after $M = 8.98$ s ($S.E. = .20$) in feedback-trials without any marker-presentation. These results matched to the trained target duration of 8 s, and were in line with participants' reports of having been able to successfully memorize the critical target interval.

Fig. 2 illustrates participants' mean time-reproduction for baseline-trials presented at the beginning (pre-baseline), and end of each

Fig. 1. Post-rating of distracter stimuli (white bar: neutral/simple stimuli; black bar: neutral/complex stimuli; gray bar: unpleasant/complex stimuli). All subjective ratings were given on 9-point rating scales according to the valence (1—unpleasant; 5—neutral; 9—pleasant), arousal level (1—low; 9—high), and perceptual complexity (1—simple; 9—very complex) of distracters. Values indicate mean (*M*) ± standard error (*S.E.*); *$p < .05$; **$p < .01$; ***$p < .001$; n.s.: not significant ($p > .05$).

Fig. 2. Pooled timing performance for distracter-trials (with presentation of neutral/simple, neutral/complex, and unpleasant/complex distracters), and baseline-trials (without any distracter presentation) presented at the beginning (pre-baseline) or end of each experimental block (post-baseline). Within the figure, the trained target duration of 8 s (solid line), and the memorized target interval (i.e., mean of timing performance in all baseline-trials without temporal distraction; dashed line) are depicted. Error bars denote standard error (S.E.).

experimental block (post-baseline), and for distracter-trials with presentations of neutral/simple, neutral/complex, or unpleasant/complex distracters. Descriptive analysis revealed mean time-reproductions of $M = 10.00 s$ ($S.E. = .18$) in baseline-trials, $M = 10.24 s$ ($S.E. = .23$) in trials with neutral/simple distracters, $M = 11.32 s$ ($S.E. = .26$) in trials with neutral/complex distracters, and of $M = 11.33 s$ ($S.E. = .26$) in trials with presentations of unpleasant/complex distracters (see also Table 1).

For the statistical analysis of the accuracy of absolute time-reproduction data, a 4×4 repeated measures ANOVA with the within-subject factors 'experimental condition' (baseline, neutral/simple, neutral/complex, and unpleasant/complex distracters) and 'block number' (block 1 to 4) was conducted. The analysis revealed a significant main effect of 'experimental condition' ($F(3, 60) = 18.35$, $p < .001$), but no main effect of 'block number', and no interaction between factors ($p > .05$). Bonferroni–Holm-corrected post-hoc paired t-tests revealed significant differences in reproduced durations for the comparison of data from baseline and neutral/complex distracter conditions ($t(83) = 7.62$, $p < .001$), baseline and unpleasant/complex distracter conditions ($t(83) = 7.02$, $p < .001$), neutral/simple and neutral/complex distracter conditions ($t(83) = 6.47$, $p < .001$), and for the comparison of neutral/simple and unpleasant complex distracter conditions ($t(83) = 7.38$, $p < .001$). Significant differences in time-reproduction were neither observed for the comparison of time-reproductions from baseline and neutral/simple distracter conditions, nor for the comparison of time-reproductions from neutral/complex and unpleasant/complex distracter conditions ($p > .05$).

Fig. 3 illustrates the mean of distracter-induced overproductions of temporal durations. Data in this figure represent the mean difference of participants' time-reproduction performance for each of the three distracter-subsets, compared to their time-reproduction across baseline-trials. Compared to baseline, neutral/simple distracters induced overproductions of $M = .23 s$ ($S.E. = .15$), whereas neutral/complex and unpleasant/complex distracters produce overproductions of $M = 1.31 s$ ($S.E. = .17$) and $M = 1.33 s$ ($S.E. = .19$), respectively (Fig. 3). To test whether the observed overproductions were equal to the fixed distracter duration of 2 s, individual time shifts induced by neutral/complex and unpleasant/complex distracters were further analyzed using one-sample t-tests ($p < .05$, two-sided), since these two distracter conditions produced time-reproductions being significantly different from the baseline condition. The analysis revealed distracter-induced overproductions that were significantly shorter than the distracter duration of 2 s for both neutral/complex ($t(83) = 3.99$, $p < .001$), and unpleasant/complex distracters ($t(83) = 3.57$, $p < .01$).

Finally, effects of perceptual complexity and arousal on participants' time-reproduction data were analyzed using Pearson product moment correlations. Therefore, absolute time-reproduction data were correlated with subjective distracter ratings of perceptual complexity and arousal. The analysis revealed a significant correlation between participants' mean time-reproductions and their complexity ratings for presented distracter stimuli ($r = .256$; $p < .05$). Although we reported a significant positive correlation between participants' ratings of perceptual complexity and arousal ($r = .725$; $p < .001$), no significant correlation

Table 1

Summary of fitted parameters for peak time (sec), peak amplitude (responses/min), and width (sec), as well as r^2-values (r^2-values of '1' indicate a perfect fit) of pooled time response functions for the different experimental conditions (baseline, neutral/simple, neutral/complex, and unpleasant/complex distracter condition). For reasons of comparison, also participants' absolute (unfitted) time-reproduction values (in sec) are depicted. Values and parameters indicate mean (M) ± standard error ($S.E.$).

| Condition	Absolute time-reproduction (s)	Peak time (s)	Peak amplitude (responses/min)	Width (s)	r^2
Baseline	10.00 ± .18 S.E.	9.88 ± .19 S.E.	24.80 ± 1.45 S.E.	1.35 ± .07 S.E.	.92 ± .01 S.E.
Neutral/simple distracters	10.24 ± .23 S.E.	10.22 ± .24 S.E.	33.62 ± 1.72 S.E.	1.07 ± .06 S.E.	.96 ± .01 S.E.
Neutral/complex distracters	11.32 ± .26 S.E.	11.43 ± .27 S.E.	30.14 ± 1.86 S.E.	1.21 ± .09 S.E.	.92 ± .01 S.E.
Unpleasant/complex distracters	11.33 ± .26 S.E.	11.37 ± .29 S.E.	30.87 ± 1.84 S.E.	1.20 ± .07 S.E.	.93 ± .01 S.E.
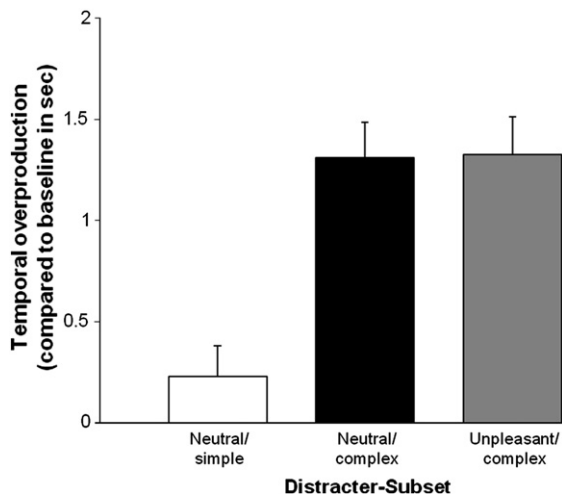
Fig. 3. Temporal overproductions observed after presentation of neutral/simple (white bar), neutral/complex (black bar), or unpleasant/complex distracters (gray bar). Data represent the mean absolute difference of participants' time-reproductions for each of the three distracter conditions, compared to their mean timing performance in all baseline conditions (i.e., mean of pre- and post-baselines). Error bars denote standard error (S.E.).

was observed for the comparison of time-reproduction data with participants' subjective arousal ratings ($p > .05$).

2.2.3. Time response functions and precision of timing performance

In addition to the analysis of absolute time-reproduction data, fitted time response functions were applied to our data using MATLAB 7.8.0 (R2009a, TheMathWorks, Inc., Natick, MA, USA). Time response functions provide an ideal illustration of the accuracy and precision of participants' time-reproductions in baseline-trials and trials with presentation of different distracter-subtypes (see Fig. 4). Even more important, time response functions are regularly reported in animal interval timing studies (Buhusi, 2012; Buhusi & Meck, 2000, 2006a,b; Olton et al., 1988; Roberts, 1981), thus the calculation of these functions allows for more direct comparisons of our data with data from animal timing studies investigating timing in the seconds-to-minute range (interval timing). Comparable to these studies, we divided the maximum trial length (20 s) into subintervals (bins) of 1 s duration, and determined the response-frequency (responses/min) for each bin by summating timing responses for each experimental condition (and across experimental blocks), and
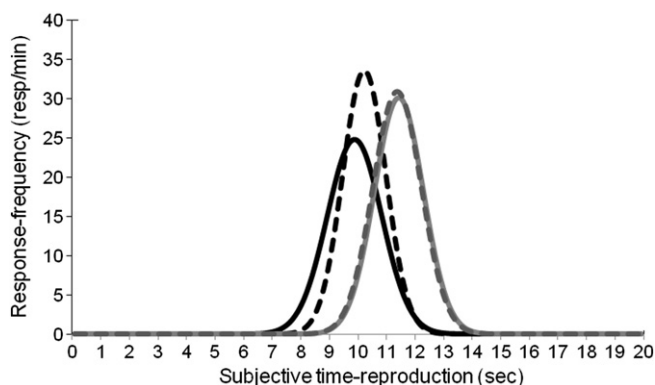
Fig. 4. Illustration of Gaussian-fitted pooled time response functions for the different experimental conditions of this study (black solid line: baseline condition; black dashed line: neutral/simple distracter condition; gray solid line: neutral/complex distracter condition; gray dashed line: unpleasant/complex distracter condition). A summary of fitted parameters (peak time, peak amplitude, and width) and corresponding Goodness-of-fit-values (r^2) is provided in Table 1.

then dividing the resulting bin-count by the absolute number of trials for this condition. Using the MATLAB curve fitting toolbox, Gaussian-fits (equation: $a \times \exp(-((x - b)/c)\verb|^|2))$) were obtained from response-frequency data using the nonlinear least square method with further refinement by minimizing least absolute residuals. Individual fits were approved with Goodness-of-fit-tests, which on average revealed a very good quality of the fits (adjusted $r^2 \geq .92$). Parameters (a, b, c) corresponding to the accuracy of time-reproduction (peak time, b), maximum response rate at peak time (peak amplitude, a), and precision of timing (width, c) were extracted from individual fits, and were averaged across participants to obtain pooled time response functions for all experimental conditions (Fig. 4). Table 1 summarizes the means and standard errors for fitted parameters of peak time, peak amplitude, and width (as they were obtained from time response functions), and contrasts these data to means and standard errors for absolute time-reproduction data. In addition, adjusted r^2-values (indicating the quality of corresponding fits) are provided.

For statistical analyses of the accuracy (peak time) and precision (amplitude and width) of individual time response functions, separate 4×4 repeated measures ANOVAs with the within-subject factors 'experimental condition' (baseline, neutral/simple, neutral/complex, and unpleasant/complex distracters) and 'block number' (block 1 to 4) were conducted for fitted parameters of peak time, amplitude, and width.

The statistical analysis of peak times was highly comparable to the analysis of absolute (unfitted) time-reproduction data, and revealed a significant main effect of 'experimental condition' ($F(3, 60) = 22.74$, $p < .001$), but no main effect of 'block number', and no interaction between factors ($p > .05$). Bonferroni–Holm-corrected post-hoc paired t-tests revealed significant differences in peak time for the comparison of data from baseline and neutral/complex distracter conditions ($t(83) = 8.96$, $p < .001$), baseline and unpleasant/complex distracter conditions ($t(83) = 6.94$, $p < .001$), neutral/simple and neutral/complex distracter conditions ($t(83) = 6.78$, $p < .001$), and for the comparison of neutral/simple and unpleasant/complex distracter conditions ($t(83) = 6.15$, $p < .001$). Significant differences in peak time were neither obtained for the comparison of parameters from baseline and neutral/simple distracter conditions, nor for comparisons of parameters from neutral/complex and unpleasant/complex distracter conditions ($p > .05$).

Analysis of peak amplitudes revealed a significant main effect of 'experimental condition' ($F(3, 60) = 2.89$, $p < .05$), but no main effect of 'block number', and no interaction between factors ($p > .05$). Bonferroni–Holm-corrected post-hoc paired t-tests revealed the main effect of 'experimental condition' to be due to a significant difference in peak amplitude for the comparison of time response functions for the baseline condition ($M = 24.80$ resp/min, S.E. $= 1.45$) and the neutral/simple distracter condition ($M = 33.62$ resp/min, S.E. $= 1.72$; $t(83) = 4.26$, $p < .0011$), and for the comparison of time response functions for the baseline condition and the unpleasant/complex condition ($M = 30.87$ resp/min, S.E. $= 1.84$; $t(83) = 2.72$, $p < .01$). However, peak amplitude was not significantly different ($p > .05$) between the baseline condition and the neutral/complex condition ($M = 30.14$ resp/min, S.E. $= 1.86$).

Analysis of the width of time response functions revealed a significant main effect of 'experimental condition' ($F(3, 57) = 3.37$, $p < .05$), but no main effect of 'block number', and no interaction between factors ($p > .05$). Bonferroni–Holm-corrected post-hoc paired t-tests demonstrated the main effect of 'experimental condition' to be due to a significant difference in the observed width of time response functions when comparing parameters from the baseline ($M = 1.35$ s, S.E. $= .07$) and the neutral/simple distracter condition ($M = 1.07$ s, S.E. $= .06$; $t(83) = 3.57$, $p < .001$). However, no significant differences ($p > .05$) were observed by comparing width-parameters from the baseline condition with parameters from the neutral/complex ($M = $

1.21 s, *S.E.* = .09) or unpleasant/complex (*M* = 1.20 s, *S.E.* = .07) distracter condition. Thus, compared to the baseline condition, the overall time response function for the neutral/simple distracter condition showed an increased amplitude and was slightly narrower. By contrast, the overall time response function for perceptually complex stimuli showed a peak amplitude and width in magnitudes of somewhere in between the values obtained for the baseline and the neutral/simple distracter condition (see Table 1).

2.3. Discussion

The present study investigated the extent to which subjectively rated distracter dimensions of valence, arousal or perceptual complexity account for distracter-induced misperceptions of critical target durations. More precisely, it had been investigated whether subjectively rated distracter dimensions of arousal and valence (related to levels of emotionality), or rather stimulus complexity, as a confounder, produce distortions in participants' reproduction of a previously trained target interval. By systematically defining distinct subsets of visual distracter stimuli, we intended to dissociate non-temporal effects of arousal, valence, and stimulus complexity on human interval timing performance.

Comparable to previous studies, our results demonstrated intrinsic stimulus features to critically affect subjective time distortions (e.g., van Wassenhove et al., 2008). However, our results showed temporal overproductions in a magnitude of less than distracter duration only for complex distracters. Stimulus dimensions of arousal and valence produced no temporal misperceptions. Additionally, subjective arousal levels were not significantly correlated with time-reproduction data, even though a significant correlation between subjective ratings of arousal and stimulus complexity had been observed. Thus in our study, stimulus complexity, rather than the arousal level or valence of distracters (indicative of the emotionality of stimuli) was accountable for distracter-induced temporal distortions in human interval timing. Within an internal clock framework, complexity-dependent overproductions of previously trained target durations can be hardly explained by arousal-dependent mechanisms of an internal clock (Angrilli et al., 1997; Block, 1992; Droit-Volet et al., 2004; Effron et al., 2006; Gil et al., 2007; Noulhiane et al., 2007). However, as we will discuss below, complexity-dependent modulations in subjective time-reproduction are highly compatible to the notion of a stimulus-dependent time- or resource-sharing mechanism (Buhusi, 2012; Buhusi & Meck, 2009; Fortin, 2003; Fortin & Massé, 2000; Leyeune, 1998, 2000; Rousseau et al., 1984).

2.3.1. Time-reproduction and time response functions

During training, participants correctly responded to the trained target duration of 8 s in marker-trials and feedback-trials without any marker presentation. In addition, all participants explicitly reported having been able to successfully memorize the trained target duration. However, during the experimental session, participants' time-reproductions in baseline-trials substantially differed from the trained target duration, and revealed an overall time-reproduction of 10 s. This large departure (25%) of timing from the critical target duration might best be explained by difficulties in memorizing the correct target interval. This explanation becomes supported by careful inspection of baseline-responses in Fig. 2, where mean time-reproductions in pre- and post-baseline-trials are depicted for each of the four experimental bocks. In this figure, the deviation from the trained target duration becomes apparent already within the first five experimental baseline-trials (Fig. 2: pre-baseline, block 1) performed after the training (i.e., before any distracters had been presented). Most importantly, the memorized target interval of 10 s remained nearly constant throughout the course of the entire session, demonstrating the stability of the memorized target representation. Therefore, responses in experimental baseline-trials were not tainted by other processes than timing and

participants' performance in experimental baseline-trials thus proved to be appropriate for testing distracter-induced mechanisms of temporal misperceptions, even though the memorized duration was not identical to the trained target duration. Currently, we can only speculate about a reason for the observed difference of trained compared to memorized temporal durations. One apparent reason might be, that participants added the marker duration (1 s) and the latency of their timing responses in feedback-trials (.98 s) on their mental representation of the critical target interval. This strategy would result in a memorized time representation of 9.98 s, which is quite comparable to participants' mean baseline performance of 10 s as it was observed across all experimental blocks of trials (see Fig. 2).

Fitted time response functions confirmed the pattern of time-reproductions (i.e., smoothly increasing response density to a peak near criterion time, followed by a smooth and symmetrical decrease of the response rate to near zero levels of responding) as it has been previously reported for rodents and birds (Cheng & Westwood, 1993; Church, Meck, & Gibbon, 1994; Gibbon, 1977; Gibbon & Church, 1990), or human subjects (Hinton & Meck, 2004; Lustig & Meck, 2005; Rakitin et al., 1998; Wearden & McShane, 1988). Compared to participants' pooled time response function for the neutral/simple distracter condition, the pooled time response function for the baseline condition was demonstrated to be slightly broader, and showed a decreased amplitude. By contrast, the pooled time response function for perceptually complex stimuli was shown to produce a peak amplitude and width in a magnitude of somewhere in between the values obtained for the baseline and the neutral/simple distracter condition. The observed differences in time response functions might be explained by the fact, that in our study the duration and position of presented distracters were kept fixed. It is therefore possible that participants' expectation of distracter on- and offsets implicitly helped them to anchor their time-reproductions, and thus influenced the variability of timing responses in distracter-trials.

Previous studies revealed the expectancy of a gap (or break) to influence human time perception by producing longer time-reproductions as the gap occurred later in the trial (Fortin, 2003; Fortin & Massé, 2000; Fortin et al., 2005; Tremblay & Fortin, 2003). The same effect was described, when the location of an interfering event, instead of an 'empty' gap, was varied (Fortin et al., 2005; Rousseau et al., 1984). For example, Fortin et al. (2005) presented a perceptually simple distracter stimulus in the middle of an otherwise stimulus-free target duration of 2.4 s and observed mean overproductions of the trained target duration of about *M* = .35 s (measured across distracter durations between 1 and 3 s). Such an overproduction corresponds to the magnitude of temporal overproductions as it was observed in our study for the emotionally neutral and perceptually simple distracter (*M* = .23 s). Thus, one might speculate, that in our study the observed overproduction in distracter-trials with neutral/simple distracters originated from an expectation-dependent effect on timing, and not from the characteristics of the distracter itself. However, expectation-dependent effects on timing cannot completely account for the observed complexity-dependent overproductions in distracter-trials with emotionally neutral and perceptually complex (*M* = 1.31 s), as well as emotionally unpleasant and perceptually complex distracters (*M* = 1.33 s).

2.3.2. Distracter-induced distortions of human interval timing

Our results showed temporal overproductions in a magnitude of less than distracter duration only for perceptually complex distracters. Within an internal clock framework, complexity-dependent overproductions of previously trained target durations can be hardly explained by arousal-dependent mechanisms of an internal clock (Angrilli et al., 1997; Block, 1992; Droit-Volet et al., 2004; Effron et al., 2006; Gil et al., 2007; Noulhiane et al., 2007). Generally, increased arousal is assumed to increase the pulse rate of the internal clock's pacemaker and to produce temporal overestimations or underproductions as a

function of the arousal level of presented distracter stimuli (Angrilli et al., 1997; Buhusi & Meck, 2002; Droit-Volet et al., 2004; Effron et al., 2006; Gil et al., 2007; Noulhiane et al., 2007). However, in our study participants overproduced the critical target duration (i.e., underestimated the flow of physical time). Such distracter-induced overproductions of memorized target durations have been previously reported also for rodents and birds (Buhusi, 2012; Buhusi & Meck, 2000; Cabeza de Vaca, Brown, & Hemmes, 1994; Roberts, 1981; Roberts, Cheng, & Cohen, 1989). Recent animal timing studies (using gaps or distracters) observed a large range of temporal overproductions (Buhusi & Meck, 2006a,b; Buhusi, Paskalis, & Cerutti, 2006; Swearingen & Buhusi, 2010). Animals' timing responses could be delayed anywhere along a continuum between precise time-reproduction (run-mode, i.e., gaps or distracters were completely ignored; Buhusi et al., 2006), overproductions in a magnitude of roughly the duration of gaps or distracters (stop-mode, e.g., timing was stopped for the duration of gaps or distracters; Buhusi & Meck, 2006b; Church, 1978; Roberts, 1981; Roberts & Church, 1978), and overproductions in a magnitude of roughly the sum of durations of gaps or distracters, plus the duration preceding the onset of the interruption (reset-mode, i.e., the timing process became restarted after presentation of gaps or distracters; Buhusi et al., 2006; Cabeza de Vaca et al., 1994; Roberts et al., 1989). The observed variation in gap- or distracter-induced overproductions along a run–stop–reset continuum provides strong support for a time- or resource-sharing model of interval timing (Buhusi, 2012; Buhusi & Meck, 2009; Fortin, 2003; Fortin & Massé, 2000; Leyeune, 1998, 2000; Rousseau et al., 1984). According to this model, gaps or distracters induce a loss of accumulated pacemaker pulses due to processing resources being diverted toward the processing of the intruding stimulus or event, thus delaying the moment when the criterion number of pulses corresponded to the memorized target duration. This pulse loss was demonstrated to be proportional to the salience of the interrupting event (Buhusi, 2012). For example, in pigeons (Buhusi et al., 2002), manipulations of the contrast in brightness between a gap and the timed signal shift time response function in a great dynamic range. At 40% gap-signal contrast pigeons were minimally interrupted in their timing (run-mode), while at 100% contrast they reset their timing after the gap (reset-mode). It was argued, that less salient distracters only require few processing resources, so that most processing resources are still concentrated on the timing process. In contrast, very salient distracters require a high amount of processing resources, so that fewer resources would be available to timing, resulting in a complete loss of accumulated pulses (Buhusi, 2012). Recently, salience- and stimulus-dependent effects on timing have also been demonstrated for human participants (van Wassenhove et al., 2008; Wittmann et al., 2010). In our study, the ability to discriminate distracters from the to-be-timed stimulus (gray screen) was almost comparable for neutral/simple, neutral/complex, and unpleasant/complex distracters. Thus not the saliency, but more likely the complexity of distracters induced overproductions of memorized time intervals.

Within an internal clock framework, our data support the notion of pacemaker pulses becoming lost during distracter presentation at a rate controlled by the perceptual complexity of presented distracters. Such a loss of accumulated pulses might best be explained by an attention-dependent 'flickering' of the clock-switch (Leyeune, 1998, 2000). Without presentation of perceptually complex distracters, attentiveness to the timing process is high enough to produce a high frequency of repetitive openings and closings of the switch ('flickering'), thus allowing an almost unhindered transfer of pulses into the accumulator. Perceptually complex distracters reduce this frequency of repetitive openings and closings of the switch, which prevents pulses from entering the accumulator.

In summary, our data suggest stimulus complexity to be responsible for distracter-induced distortions in human time-reproduction. We showed temporal distortions to depend on the perceptual complexity,

and not the arousal or valence (i.e., emotionality) of visual distracters. In situations where temporal accuracy has to be maintained despite 'noisy' and distracting natural environments, complexity-dependent changes of the internal clock's pulse-accumulation constitute an efficient and economic strategy for humans to ensure precise timing even in the presence of emotional and arousing stimuli.

Although we used a robust psychophysical paradigm that has been probed and tested previously, some methodological aspects might limit the interpretation of our results. Firstly, one should be aware that we employed an experimental paradigm with a primary timing stimulus that has to be attended to (i.e., the 'empty' interval) and a secondary distracter stimulus that was varied according to dimensions of arousal, valence, and stimulus complexity. Thus, our paradigm is different from studies where emotional stimuli were used as primary (carrier) stimuli (e.g., Angrilli et al., 1997; Block, 1992; Droit-Volet et al., 2004; Effron et al., 2006; Gil et al., 2007; Noulhiane et al., 2007). Although our paradigm allowed for a better differentiation of temporal and non-temporal factors, one cannot exclude that certain task characteristics prevent from finding effects of valence or arousal. Thus, it is questionable whether our findings are transferable to time-estimation tasks using emotional stimuli as primary (carrier) stimuli. Secondly, one cannot exclude that in our study the relatively short presentation time of distracters (2 s) favors the effects of perceptual complexity, and prevents from finding effects of valence or arousal. Finally, one might argue that participants' subjective scoring of distracter stimuli is irrelevant to the mechanisms actually at work in our protocol. Future studies should employ longer durations of target intervals and distracter stimuli, and try to dissociate subjective and objective effects of arousal and valence (or emotionality) by using advanced physiological recordings (e.g., by directly measuring emotion-related neural activity in appropriate brain regions).

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