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RESEARCH REPORT

Time perception is not for the faint-hearted? Physiological arousal does not influence duration categorisation

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Abstract
Distortions of duration perception provoked by emotion-induced arousal changes are explained by modifications of an internal clock pace. Yet, uncertainty still abounds regarding whether changes of arousal induced by physical exercise yield such temporal distortions. Here, we report two experiments aiming to test separately the impact of, on the one hand, a physical induction of arousal and, on the other hand, a task delay on duration categorisation. In Experiment 1, participants performed a duration categorisation task before and after heart-rate manipulation (increase, decrease, or no change). Duration overestimation was observed after HR manipulation, irrespective of the condition, implying that changes of physiological arousal alone cannot explain the temporal bias observed. In Experiment 2, participants performed the duration task twice without delay or arousal manipulation, and no overestimation was observed. Together, these results suggest that the overestimation observed in the context of a delayed duration categorisation task is related to a distortion of memorised standard durations caused by time lag rather than by a physiological arousal effect.

Keywords Time processing · Physiological arousal · Heart rate · Duration categorisation task

Introduction

Interval timing skills are fundamental to develop and maintain adapted behaviours (Buhusi and Meck 2005; Wittmann and Paulus 2008). An influential theoretical model posits a joint action of a pacemaker producing a succession of pulses and of an accumulator counting the number of pulses emitted over a given time period, this count determining the experienced duration (Gibbon et al. 1984; Treisman et al. 1990). This clock stage is followed by a memory stage whereby the value stored in the accumulator is compared to previously stored reference durations. This comparison ultimately produces duration estimation, leading to temporal decision, and resulting behavioural responses (Gibbon et al. 1984; Treisman et al. 1990).

As the ability to estimate duration is highly context-dependent, under- or overestimation of durations is frequently observed in humans. A wide range of factors modulates duration estimation, such as physical characteristics of stimuli (e.g. Dormal et al. 2006; Van Wassenhove et al. 2011) or availability of attentional resources (Block and Zakay 1997; Fortin and Massé 2000). According to the aforementioned model, these distortions may originate from any of the processing stages or internal clock components (Block and Zakay 2008; Matthews and Meck 2016): (1) the pulses production rhythm by the pacemaker may be increased or decreased; (2) the accumulator may occasionally miss pulses; (3) the reference interval may be distorted in long-term memory; (4) the working-memory capacity may be disturbed; or (5) the decision processes may be biased.

One of the most frequently reported factors influencing duration perception is arousal level (Penton-Voak et al. 1996; Wearden and Penton-Voak 1995). The internal pacemaker model does indeed posit that the rate of the pacemaker pulses

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is influenced by arousal (Meck 1983; Treisman et al. 1990). This way, an increase of arousal might induce a speeding-up of the internal clock system, leading to a duration overestimation (Droit-Volet and Meck 2007; Wearden 2005). In contrast, decrease in arousal might yield reduced pulse rates of the internal clock, thereby resulting in temporal underestimation (Buhusi and Meck 2002). Importantly, the definition of arousal is still widely discussed as different facets of arousal have been considered in prior studies. Arousal mainly relies on two components: (1) physiological arousal, referring to a body response denoting a state of readiness for action and involving the activation of the autonomic nervous system (Cahoon 1969; Wearden and Penton-Voak 1995); and (2) emotional arousal, referring to an emotionally induced and/or perceived psychological state (Pfaff 2006). Moreover, some authors have also considered a third arousal component, namely a cognitive/subjective arousal, denoting mental stimulation and cognitive awareness of being engaged in a task or activity (e.g. Schwarz et al. 2013). Beyond these distinctions, it is widely acknowledged that these arousal subcomponents are strongly interconnected, and that interactions among them are frequently observed. For instance, the elicitation of a cognitive arousal might in turn increase affective arousal. Moreover, even if modifications of emotional arousal always involve changes in physiological arousal, as emotional activation triggers physiological one (Schachter and Singer 1962), the reverse pattern is not always reported given that physiological arousal can be manipulated independently of any emotional context (e.g. physical exercise). The arousal induction procedure is thus an essential factor to determine which component of arousal is manipulated, and thus allows to explore the effect of a specific arousal subcomponent on other cognitive processes (e.g. duration perception). In addition to widely used subjective measures of arousal, both emotional and physiological components can be objectively assessed through reliable physiological measures like heart rate (HR) or skin conductance responses. Although several studies have demonstrated the impact of emotional arousal on duration processing by manipulating emotional stimuli (for a review, see Droit-Volet and Meck 2007; Lake et al. 2016), uncertainty remains regarding the respective contributions of physiological and emotional inductions in the resulting increase of emotional arousal.

Although some studies relied on correlational approach to understand the link between physiological arousal and temporal distortion (e.g. Lediett and Tong 1972; Meissner and Wittmann 2011; Osato et al. 1995), others experimentally manipulated physiological arousal. First, dual-task paradigms were used to increase physiological arousal, while participants had to estimate or produce durations (see Table 1). In this way, performing muscle tension exercises yielded both underestimation and under-reproduction of long durations (i.e. 24 or 48 s; Warm et al. 1967). Conversely, performing a physical activity (e.g. cycling) led to an overestimation of sub-second durations (Lambourne 2012) and under-production of 10-s interval (Vercruyssen et al. 1989), suggesting a speeding-up of the accumulation rate. Yet, the two aforementioned studies are the only ones that adequately monitored the variations in physiological arousal (i.e. measures of heart rate, HR; oxygen volume, VO_2) throughout the experiment. Another study also dissociated the influence of emotional and physiological arousal on duration processing by using negative sounds with different arousal levels (Mella et al. 2011). Negative sounds led to longer duration estimations compared to neutral ones, regardless of the arousal level. The authors thus concluded that the relation between autonomic arousal responses (assessed through skin conductance measures) and duration perception was mediated by the attentional salience of the stimuli (represented here by the emotional valence of the sound). Depending on activity type, duration range, and task used, various duration distortions have been observed, which does not fully support a direct link between physiological arousal and duration perception. Importantly, in previous studies, duration estimation was performed during arousal manipulation, so that the amount of attentional resources available for the temporal task could differ from control condition, which could potentially explain the observed duration distortions.

Second, the effect of a decrease of physiological arousal on duration estimation has been explored using meditation exercises. Although the accumulator model predicts an underestimation of duration due to a possible slowing down of pulses rate via such exercises (Buhusi and Meck 2002), participants did overestimate duration intervals after meditation exercises (Droit-Volet et al. 2015; Kramer et al. 2013; see Table 1). These results were interpreted in terms of attentional resources modulation rather than physiological arousal—i.e. meditation training may generate temporal processing improvement due to an increase of the attentional resources devoted to duration processing. Yet, as physiological parameters were not assessed via suitable measurement tools, one may argue that these findings do not mirror a genuine manipulation of physiological arousal.

Finally, other studies applied a bidirectional manipulation of physiological arousal (i.e. both increase and decrease in a within-participant design; see Table 1). Temporal estimation performances were compared when participants were performing a physically effortful task (i.e. exerting continuous force on a transducer) that requires either to increase or decrease the force applied as compared to a baseline level (Molet et al. 2011). Increased scenario led to duration overestimation, whereas force reduction led to duration underestimation. The authors argued that the physical force task increased the attention dedicated to temporal cues. Yet, again, the influence of a potential modulation of physiological arousal cannot be established due to the absence of

Table 1 Studies investigating the effect of manipulation of physiological arousal on duration perception

Manipulation direction	References	Duration task(s)	Durations range	Physiological arousal manipulation	Physiological measures	Duration task timing	Main results
Arousal increase	Lambourne (2012)	Bisection	300–600 ms	Cycling	Heart-rate VO_2	Pre- and during arousal manipulation	Overestimation during exercise
	Mella et al. (2011)	Comparison	1800–2200 ms	Negative or neutral sounds (low vs. high arousal)	Skin conductance	During arousal manipulation	Overestimation of negative sounds (whatever the arousal level)
	Vercruyssen et al. (1989)	Production	10 s	Cycling	Heart rate	Pre-, during and post-arousal manipulation VO_2	Under-production during exercise
	Warm et al. (1967)	Reproduction and verbal estimation	6, 12, 24 and 48 s	Muscle tension	None	During arousal manipulation	Underestimation and under-reproduction of 24- and 48-s intervals
Arousal decrease	Droit-Volet et al. (2015)	Bisection	4–8 s	Relaxation vs. meditation	None	Pre- and post-arousal manipulation	Overestimation after meditation
	Kramer et al. (2013)	Bisection	400–1600 ms	Meditation	None	Pre- and post-arousal manipulation	Overestimation after meditation
Combined arousal increase and decrease	Molet et al. (2011)	Bisection	2–8 s	Force exercise (increase vs. decrease)	None	During arousal manipulation	Overestimation during force increase exercise; underestimation during force decrease exercise
	Schwarz et al. (2013)	Estimation and production	8 s	Muscle vs. breath-holding exercise	Heart rate	During arousal manipulation	Overestimation during muscle and breath-holding exercises

physiological measures. In another study, estimation of 8-s intervals was assessed when participants were performing either a muscular (i.e. increased heart-rate condition) or a breath-holding (i.e. decreased heart-rate condition; Schwarz et al. 2013) exercise. HR was monitored throughout the experiment. An overestimation of the actual stimuli duration was observed in both exercise conditions compared to the control one, suggesting that duration perception was not specifically affected by HR level. Nevertheless, some aspects of the previous studies prevent firm conclusions about the effect of physiological arousal on duration perception. On the one hand, only large duration (i.e. supra-second intervals) estimations were investigated, whereas the impact of emotional arousal has most often been demonstrated with sub-second intervals in interference studies, the processing of these different durations relying on different neural networks (e.g. Mauk and Buonomano 2004). On the other hand, as mentioned above, because physiological arousal manipulation and duration estimation were concomitants, the variability in attentional resources available during the different processing steps constituted an important confound to determinate the exact role of physiological arousal.

As a consequence, two experiments were conducted in order to determine whether a physical induction of arousal modification—that is without modification of emotional arousal and of attentional resources—is sufficient to produce distortions in duration estimation. In Experiment 1, the influence of physiological arousal as measured by HR on duration perception was estimated by using a duration categorisation task before and after arousal manipulation. During this task, duration intervals in the millisecond range had to be categorised as *short* or *long* according to previously learned duration references. This categorisation task has been used in several recent behavioural, fMRI, and neuromodulation studies (e.g. De Visscher et al. 2017; Dormal et al. 2012, 2016). It ensures the presence of both high task specificity via a classical pattern of performance (e.g. the presence of a distance effect, i.e. the closer the durations, the longer and the more error prone the judgements) and task sensitivity (i.e. neither ceiling nor floor effect). Three conditions were used in a within-subject design: (1) HR increase (i.e. cycling condition), (2) HR decrease (i.e. relaxation condition), and (3) no HR change (i.e. crosswords condition). Importantly, to ensure that the level of attentional resources available to perform the duration task was equivalent during the two testing blocks and to avoid any potential attentional bias which could influence duration performance, the duration task was performed before and after but not during arousal manipulation. The first testing block corresponded to the baseline measure, while the effect of arousal manipulation was assessed by comparing the baseline with the second testing block. Moreover, for each participant, physiological arousal level was manipulated in both directions (i.e. increase and decrease) in separate sessions to minimise interference and learning. These manipulations were monitored by reliable physiological measures. According to the accumulator model, physiological arousal modulation should increase or decrease the pulses generator rate. Accordingly, duration overestimation should be observed in the HR increase condition as compared to the no HR change one, while the HR decrease condition should lead to duration underestimation. Conversely, an absence of arousal manipulation effect on duration categorisation would indicate that physiological arousal per se is not a critical factor influencing duration perception. However, the use of an offline arousal manipulation necessarily introduced a delay between the duration intervals encoding and the second categorisation block. Given the importance of controlling for any memory aspect that may modulate duration estimation, Experiment 2 was designed to test whether duration distortion might be influenced by the memory delay between two categorisation blocks.

Experiment 1

Method

Participants

Eighteen volunteers (4 left-handed, 9 females, mean age: 28 ± 3.5 years) took part in this experiment. All participants had normal or corrected-to-normal vision. The experimental protocol was approved by the Ethical Committee of the Institut de Recherche en Sciences Psychologiques of the Université catholique de Louvain (Belgium).

Material, stimuli, and task

Stimuli presentation and data collection were controlled by a Dell laptop equipped with a 15.6-inch HD screen and using E-Prime software. The viewing distance was 50 cm. HR was recorded continuously in beats per minute (bpm) during the whole experiment using a Garmin wireless heart-rate monitor (Garmin Forerunner® 405 with a sample rate of 2.4 GHz) composed of a chest belt with an infrared transmitter and a wristband receiver monitor.

The stimulus was a single black dot (diameter: 4° of visual angle) presented at the centre of the computer screen for 500, 600, 800, or 900 ms. The participants performed a duration categorisation task in which they had to decide whether each dot was presented for *short* (i.e. 500 or 600 ms) or *long* (i.e. 800 or 900 ms) durations by pressing one of two 13-cm-distant keys on a keyboard with the left index finger for *short* or the right index finger for *long* durations. Categorisation was used because it is one of the most common and dynamic perceptual mechanisms in humans, consisting in mentally grouping environmental stimuli into clusters known as categories (Freedman and Assad 2006; Mendez et al. 2011). Durations inferior to one second were used as they prevent the use of explicit counting strategies (Grondin et al. 1999). Note that the durations were chosen on the basis of previous results (Dormal et al. 2016) to ensure task sensitivity—that is, neither ceiling nor floor effect. The various presentation durations were never mentioned to the participants. Importantly, the rationale behind our approach was to avoid any possibility of reference criterion recalibration during or after the arousal manipulation phase. Indeed, in the more frequently used temporal bisection task, participants are exposed to probe durations before and after arousal manipulation (i.e. before each testing session); arousal level may thus influence reference encoding rather than the estimation performance. Conversely, in our categorisation task, duration reference categories and feedback were only presented during the learning and training phases (i.e. before the first testing session; see below for details about the procedure). With this paradigm, if the participants use a cut-off criterion on the basis of which the short/long decision is taken, an overestimation bias will correspond to an increase of short category errors combined with a decrease of long category errors, while the reverse pattern will define an underestimation bias. In this task, response latencies (RLs) corresponded to the time elapsed between stimulus offset and response key press.

Procedures

HR manipulation Three HR levels were measured: before the first testing block (i.e. T1) considered as the baseline, before the second testing block (i.e. T2; at the end of the manipulation condition; 14 min after T1), and at the end of the second testing block (i.e. T3; 5 min after T2; Fig. 1a). A significant difference between T1 and T2 will indicate that the physiological arousal manipulation is efficient (i.e. that an increase or decrease of HR is measured just before the temporal categorisation task), while a significant difference between T1 and T3 will ensure that the modification of HR level is still present at the end of the duration task.

Each participant performed three sessions corresponding to the three HR manipulations (Fig. 1a): (1) the cycling condition aiming to increase HR, (2) the relaxation condition aiming to decrease HR, and (3) the fill-in crosswords condition, chosen as a control condition that should not affect HR. In the cycling condition, participants had to bike on an ergometer cycle (117 × 68 × 39 cm; YF90 Tecnovita, BH®). During a 1-min period, the speed of each participant was adapted to double their baseline HR level. They then had to maintain this rhythm over an 8-min period. In the relaxation condition, participants were lying on a fitness floor mat and were asked to follow relaxation instructions delivered via stereo headphones. A French adaptation of Bernstein and Borkovec (1973) instructions for brief muscular relaxation (Van Rillaer 1997) was used. Participants were instructed to tense and release their muscles one by one (feet, calves, thighs, hand, forearms, arms, shoulders, back, chest, neck, eyebrows, eyes, jaw) and to pay attention to proprio- and interoceptive sensations provoked by the release of their muscular tensions. This procedure was chosen as previous studies reported that it leads to HR decrease (e.g. Barlow et al. 1984; Carlson et al. 1990; Michelson et al. 1990). Finally, in the crosswords condition, participants had to realise word-searching puzzles in which they had to find

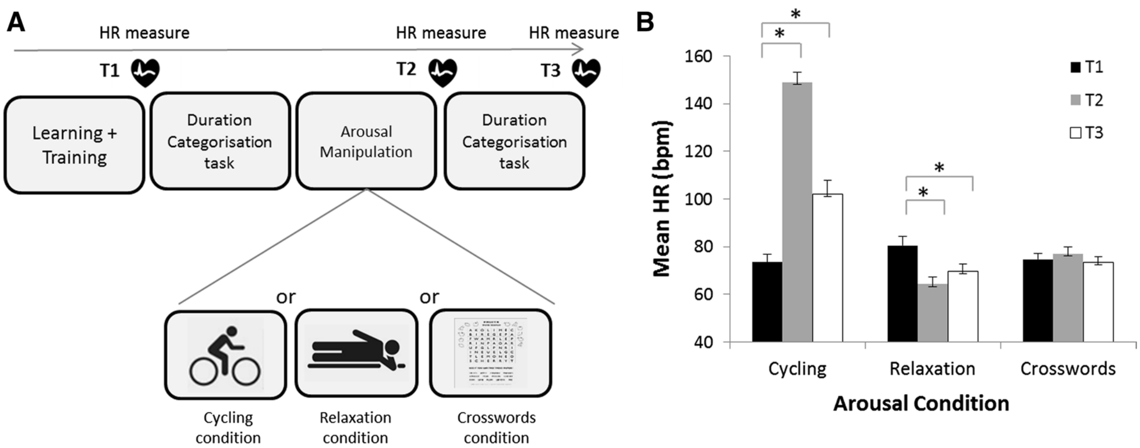

Fig. 1 **a** Schematic representation of the temporal structure of Experiment 1. Each participant carried out the four steps (i.e. learning and training, pre-testing, arousal manipulation, and post-testing) three times. In the categorisation task, participants had to decide whether the dot was presented for a short or long duration. The three experimental manipulations (i.e. cycling, relaxation, or crosswords) were carried out on three different days in a counter-balanced order. **b** Mean HR ± SE (in beat per minutes) as a function of CONDITION (cycling, relaxation vs. crosswords) and TIME (T1, T2 vs. T3). Asterisks indicate a significant difference ($p < .05$)

and mark all the words, among a given list containing 15 words, hidden inside a grid presented on A4 sheets. The instructions insisted on the need to perform crosswords in a constant but moderate rhythm. Each manipulation condition lasted for 9 min. The three testing sessions took place on separate days to minimise learning effect, and their order was counter-balanced across participants such that each condition preceded and followed the others equally often.

Duration task Each session consisted in two duration categorisation tasks (Fig. 1a): a first task performed before HR manipulation (pre-manipulation block) and a second one directly after HR manipulation (post-manipulation block). In the pre-manipulation block, participants first underwent a learning phase in which they were instructed to carefully observe 12 trials of each duration category (i.e. 12 trials of 500 and 600 ms randomly presented for the *short* durations followed by 12 trials of 800 and 900 ms randomly presented for the *long* durations); the presentation durations were not mentioned. This allowed the participants to encode the standards into reference memory. Then, they carried out a training phase with feedback during which 12 trials (6 for each duration, in a randomised order) were presented, and they were required to categorise each single dot as being *short* or *long* by pressing one of the same two keys as mentioned before. A visual feedback was given after each trial regarding the accuracy of the categorisation. Finally, participants performed the categorisation task without feedback with 64 trials, corresponding to 16 randomly mixed trials for each duration. The participants had a maximum of 2000 ms to answer, as soon as an answer was given, the next trial started. In the post-manipulation block, participants had again to perform the categorisation task with 64 trials without feedback. The task format was identical except that the standards were not presented again. This prevented participants from recalibrating their reference memory of the standards under the manipulated arousal level. The categorisation task lasted for less than 5 min.

Results

Manipulation check: HR analysis

A first analysis of variance (ANOVA) was carried out on the mean HR with CONDITION (cycling, relaxation vs. crosswords) and TIME (T1, T2 vs. T3) as within-subject variables. A significant main effect of CONDITION was revealed ($F(2, 34) = 63.760$, $p < .001$, partial $\eta^2 = .789$). The cycling condition (mean HR ± SD: 108.2 ± 16.9) was higher than the relaxation (71.6 ± 12.9) and crosswords conditions (75.0 ± 10.9; $t(17) = 10.134$, $p < .001$ and $t(17) = 7.567$, $p < .001$, respectively), which did not differ ($t(17) = 1.384$, $p = .184$). A main effect of TIME was also found ($F(2, 34) = 91.693$, $p < .001$, partial $\eta^2 = .844$), revealing that all times differed from each other regarding HR (T1: 76.3 ± 11.3, T2: 96.8 ± 10.8, T3: 81.7 ± 11.9; all p values $< .02$). Importantly, these main effects were qualified by a significant CONDITION by TIME interaction ($F(4, 68) = 164.225$, $p < .001$, partial $\eta^2 = .906$; Fig. 1b). In the cycling condition, both T2 (149.9 ± 18.2) and T3 (102.0 ± 13.9) were higher than T1 (73.6 ± 13.9; $t(17) = 20.693$, $p < .001$, and $t(17) = 6.338$, $p < .001$, respectively), while in the relaxation condition, both T2 (64.3 ± 12.6) and T3 (69.8 ± 12.8) were smaller than T1 (80.6 ± 16.2; $t(17) = 7.388$, $p < .001$, and $t(17) = 5.296$, $p < .001$, respectively). Direct T2 versus T3 comparisons revealed a significant difference for both cycling ($t(17) = 13.141$, $p < .001$) and relaxation ($t(17) = -2.627$, $p = .018$) conditions. Moreover, no significant difference was observed in the crosswords condition (T1: 74.4 ± 11.2, T2: 77.1 ± 11.6, T3: 73.3 ± 11.6; all p values $> .2$).

Duration categorisation analysis

An ANOVA was first carried out on the correct mean RLs with CONDITION (cycling, relaxation vs. crosswords), DURATION (short vs. long) and BLOCK (pre- vs. post-manipulation) as within-subject variables. Significant main effects of DURATION ($F(1, 17) = 15.154$, $p = .001$, partial $\eta^2 = .471$) and BLOCK ($F(1, 17) = 16.515$, $p = .001$, partial $\eta^2 = .493$) were observed. Long durations (mean RLs ± SD: 285 ± 76.1 ms) were globally processed faster than short ones (332 ± 49.2 ms), and participants were faster in the post-manipulation block (297 ± 60.5 ms) than in the pre-manipulation block (321 ± 59.5 ms). No other main effect or interactions were found (all p values $> .1$).

Second, a similar ANOVA on the mean error rate (ER) revealed a significant main effect of DURATION ($F(1, 17) = 6.216$, $p = .023$, partial $\eta^2 = .268$). Participants made significantly more errors for long durations (mean ER ± SD: 16.9 ± 8.7%) than for short durations (10.1 ± 6.2%). A significant interaction between DURATION and BLOCK was also observed ($F(1, 17) = 16.401$, $p = .001$, partial $\eta^2 = .491$). For short durations, more errors were made in the post-manipulation block (12.8 ± 8.1%) compared to the pre-manipulation block (7.5 ± 4.4%; $t(17) = 4.045$, $p = .001$), whereas the reverse effect was observed for long durations (pre-manipulation: 19.4 ± 9.9%, post-manipulation: 14.5 ± 7.5%; $t(17) = 2.530$, $p = .022$; Fig. 2a). Importantly, no significant interaction with CONDITION was observed (all $F < 1$; Fig. 2b). No other main effect or interactions were found (all p values $> .1$).

To detect a possible effect of arousal present at the beginning of the task which could be masked or mitigated by the decrease/increase of arousal level over time, complementary ANOVAs were carried out separately for the first half

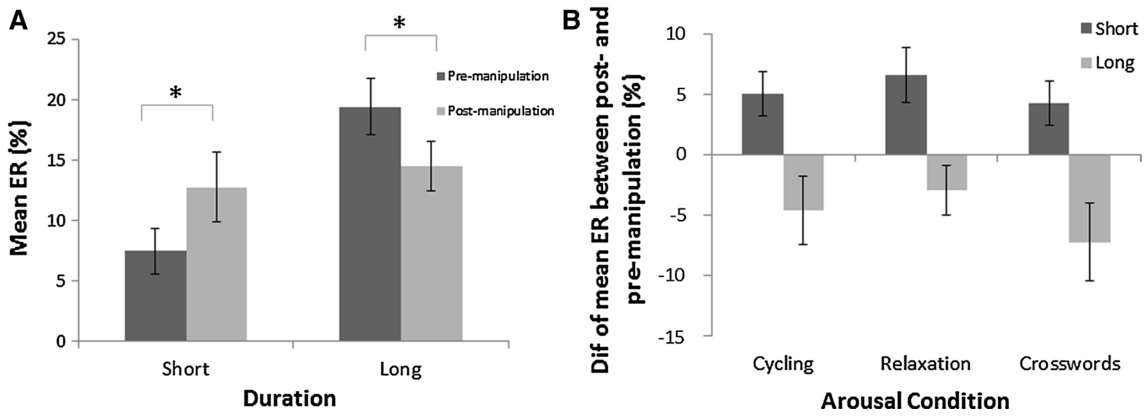

Fig. 2 Experiment 1: **a** Mean ER (± SE) as a function of DURATION (short vs. long) and BLOCK (pre- vs. post-manipulation). Asterisks indicate a significant difference ($p < .05$). **b** Mean difference of ER (in %) between post- and pre-manipulation of arousal (± SE) as a function of CONDITION (cycling, relaxation vs. crosswords) and RESPONSE (short vs. long). The absence of a significant interaction indicates that the overestimation bias was present whatever the condition

(i.e. 32 first trials) and the second half (i.e. 32 last trials). Importantly, similar results were observed for halves 1 and 2, and no interaction with CONDITION was revealed (all *p* values > .70), suggesting the presence of duration overestimation whatever the arousal condition for both halves.

Discussion of Experiment 1

Significant increase and decrease in HR were respectively reported in the cycling and relaxation conditions, while no change was observed in the crosswords condition. The manipulation of the physiological arousal was thus efficient and persisted during the whole post-manipulation duration tasks, as demonstrated by significant T1–T3 differences in both conditions.

In the post-manipulation testing, a duration overestimation (i.e. more errors for the *short* category combined with fewer errors for the *long* one, corresponding to a rightward displacement of the decisional cut-off criterion) was present in each condition, suggesting that this bias is independent of HR modification. Consequently, our results confirm that HR level is not a good predictor of temporal distortions and that physical induction of arousal alone did not significantly influence duration estimation performance. These findings fit with the results of Schwarz et al. (2013) who reported a similar overestimation when participants had to judge the duration of supra-second intervals, while they performed muscle or breath-holding exercises. Similar conclusions can be extended to a categorisation task using sub-second durations. While the physical induction of arousal manipulation was less efficient at the end of the duration task, the absence of arousal effect cannot be explained by a dilution of this effect over time, as similar results were observed when comparing performances at the beginning (i.e. Block 1) and at the end (i.e. Block 2) of the duration categorisation task.

However, a remaining issue is the explanation of this temporal bias consistently observed, independently of the experimental condition. A hypothesis is that the retention delay between the two categorisation tasks, combined with an irrelevant and interfering task (here, cycling, relaxation, or crosswords), would distort memorised standard durations, leading to duration overestimation. Indeed, previous studies have shown that the inclusion of a retention delay between learning and testing phases, during which an interference task was performed, affected temporal judgement accuracy (e.g. McCormack et al. 2004; Ogden et al. 2008; Rattat and Droit-Volet 2005). Similarly, the direct comparison of immediate versus remote estimation of duration intervals indicated a systematic overestimation of duration when a delay is added before the response is made (Vitulli and Crimmins 1998; Vitulli and Nemeth 2001; Zakay and Fallach 1984). Experiment 2 was thus designed to address this issue, using a similar duration categorisation task but without time lag between the two tests. Would the combination of a retention delay between the two categorisation tasks and the presence of an interfering task be responsible for the systematic duration distortion observed in Experiment 1, no overestimation bias should be found in Experiment 2.

Experiment 2

Materials and methods

Participants

Eighteen volunteers (3 left-handed, 10 females, mean age: 27 ± 3.6 years) took part in this experiment. They all had normal or corrected-to-normal vision and had not participated in Experiment 1. The experimental protocol was approved by the Ethical Committee of the Institut de Recherche en Sciences Psychologiques of the Université catholique de Louvain.

Stimuli, task, and procedure

The stimuli and procedure of the duration categorisation task were identical to those in Experiment 1, except that each participant performed only one session consisting of two duration categorisation tasks (i.e. Blocks 1 and 2) carried out consecutively without delay and HR manipulation between the two testing.

Results

An ANOVA was performed on the mean correct RLs with DURATION (short vs. long) and BLOCK (1 vs. 2) as within-subject variables. Significant main effects of DURATION ($F(1, 17) = 96.753$, $p < .001$, partial $\eta^2 = .851$) and BLOCK ($F(1, 17) = 9.096$, $p = .008$, partial $\eta^2 = .349$) were observed. *Long* durations (mean RLs ± SD: 291 ± 72.7 ms) were processed faster than *short* durations (387 ± 70.8 ms), and Block 2 (323 ± 66.6 ms) was performed faster than Block 1 (356 ± 76.9 ms). No significant interaction was observed ($F(1, 17) = 4.001$, $p = .062$, partial $\eta^2 = .191$).

A similar ANOVA on the mean ER revealed no main effect of DURATION ($F(1, 17) = 0.221$, $p = .645$, partial $\eta^2 = .013$) and SESSION ($F(1, 17) = 3.655$, $p = .073$, partial $\eta^2 = .177$). Importantly, the interaction was not significant ($F(1, 17) = 0.522$, $p = .480$, partial $\eta^2 = .030$).

Discussion of Experiment 2

No overestimation was observed in Experiment 2, which supports the idea that the delay induced by arousal manipulation combined with an interfering task may have yielded a distortion of the memorised durations in all three conditions of Experiment 1 (e.g. McCormack et al. 2004; Ogden et al. 2008; Vitulli and Nemeth 2001).

General discussion

An overestimation of stimulus duration has been consistently reported with various emotional materials (for reviews, see Droit-Volet and Meck 2007; Lake et al. 2016), an effect that has been attributed to the increase of arousal level induced by emotional stimuli perception, speeding up the internal clock. In other words, as the rate of the pacemaker is increased, more time units are accumulated and duration is estimated as longer (e.g. Gil and Droit-Volet 2012). However, it is still unknown whether the physical induction of arousal alone, without changes in the emotional context, can induce similar under- or overestimation of durations. To clarify this question, the influence of physiological arousal level on duration processing was directly evaluated in three experimental conditions, respectively, increasing, decreasing, and maintaining HR, the most widely used and reliable measure of physiological arousal. Participants had to categorise the duration presentation of a dot as short or long, before and after arousal manipulation.

First, HR measures in Experiment 1 confirmed the efficiency of physical induction of arousal as cycling, relaxation, and crosswords conditions respectively led to increased, decreased, or unchanged HR. Importantly, a similar duration overestimation was observed in all conditions, suggesting that the level of arousal induced by physical manipulation does not modulate duration estimation performance. This result clarifies previous correlational studies reporting no links between physiological measures and duration estimation accuracy (e.g. Curton and Lordahl 1974; Osato et al. 1995). The absence of difference between conditions is not a mere null effect, but rather crucially underlines the presence of a systematic and significant overestimation bias observed whatever the arousal manipulation, which further supports our conclusions that this temporal interval distortion was not due to the physical induction of arousal alone. It also lends some support to recent work in which no difference was observed in the estimation of supra-second durations between decreased HR (i.e. breath-holding) and increased HR (i.e. muscle exercise) conditions (Schwarz et al. 2013). Moreover, as similar overestimation of duration was observed after both decreased or increased physiological arousal manipulation, these changes being objectified by a reliable physiological measure (e.g. Lang et al. 1993), our results suggest that duration distortions described in the few studies in which the physiological level was also manipulated by physical exercise or meditation (Kramer et al. 2013; Vercruyssen et al. 1989; Warm et al. 1967) may not be determined by the physical induction of arousal itself, but rather by other uncontrolled attentional or mnesic factors. For example, in most prior studies, arousal manipulation was performed *online* (i.e. concurrently with duration processing). To rule out the limits of this method, Experiment 1 was based on an *offline* arousal level manipulation (i.e. separated from the duration processing itself). This decision was made for two main reasons: (1) as the amount of attention allocated to duration processing may affect performance (e.g. Lui et al. 2011; Zakay and Block 1997), it is important to control this variable across the different conditions. Hence, *offline* manipulation guarantees that the allocation of attentional resources in the duration task was not disturbed by a secondary task and was thus similar in every condition; (2) *offline* manipulation ensures a long-lasting modification of HR (increase or decrease was still present at the end of the duration categorisation task) that covers all the steps involved in duration processing as proposed by classical models (i.e. accumulation, comparison, decision; e.g. Church 1984; Treisman et al. 1990). This *offline* manipulation was also used to explore the influence of emotional context on duration processing (e.g. Droit-Volet et al. 2010, 2011), which can thus be more directly compared with the present results. Therefore, the systematic overestimation observed in the three conditions cannot be explained by attentional artefacts influencing performance during the post-manipulation duration task. Moreover, as a similar duration overestimation was present in the control crosswords condition, difference in terms of subjective arousal level, as proposed by Schwarz et al. (2013), cannot explain the duration distortions observed here. Indeed, if an increase of subjective arousal seems plausible in the cycling and relaxing conditions, performing crosswords without time or accuracy pressure should not modify subjective arousal. Finally, the methodological choice to use a categorisation task instead of a probe comparison task, and in particular the fact that learning and training (with feedback) phases were not repeated after the arousal induction manipulation, ensured that participants did not recalibrate the reference duration under the manipulated arousal level. However, a standard recalibration due to the successive exposure to short/long probes along the testing session (i.e. the influence of previous trial) cannot be completely excluded. Yet, we have no rationale to believe that this recalibration would have varied across experimental conditions and sessions, and this interpretation can therefore not explain the systematic duration over-estimation observed in the second session (i.e. after arousal manipulation).

As physiological arousal changes did not explain the overestimation observed in Experiment 1, we reasoned that the presence of a delay (i.e. about 9 min) between the encoding stage and the second categorisation task, combined with an irrelevant interfering task, might provoke a distortion of memorised reference durations resulting in the temporal bias observed. Indeed, both in children (Rattat and Droit-Volet 2005) and adult humans (Rattat and Droit-Volet 2010; Zakay and Fallack 1984), the inclusion of a delay between retention and testing phases led to a systematic higher variability in the temporal performance pattern. Here, the categorisation task requires comparing, for each trial, the value currently stored in the accumulator with values previously stored in reference memory and associated with the two categories of durations presented during the learning phase. Accordingly, the delay related to HR manipulation in Experiment 1, combined with the interfering task requiring attentional resources, might have distorted the values stored in reference memory, leading to the systematic overestimation observed. In order to test this proposal, participants performed the same categorisation task twice consecutively without break in Experiment 2. There was no duration overestimation, suggesting that the temporal bias observed in all conditions of the Experiment 1 was caused by the temporal delay combined with the interfering task introduced between the encoding phase and the second categorisation task. Strikingly, a similar effect has been reported when participants had to perform a computer game between learning and testing phases (Rattat and Droit-Volet 2010). Accordingly, these findings lend some support to the idea that retention delay, combined with an interference task after the initial encoding of standard durations, does affect the consolidation of these intervals in reference memory (Ogden et al. 2008; Rattat and Droit-Volet 2010). However, as the two factors were not independently manipulated in this study, firm conclusions cannot be drawn and future studies should test this assumption.

To conclude, our findings suggest that (1) the temporal distortion observed during the second performing of the categorisation was due to the retention delay and that (2) the physical induction of arousal alone, regardless of emotional context, does not explain the temporal bias induced by emotional materials in previous studies.

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Compliance with ethical standards

Conflict of interest All the authors declare that they have no conflict of interest.

Ethical standard All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards.

Informed consent Informed consent was obtained from all individual participants included in the study.

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