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# The heart beat does not make us tick: The impacts of heart rate and arousal on time perception

**Marcus A. Schwarz · Isabell Winkler · Peter Sedlmeier**

**Abstract** According to popular models of human time perception, variations in prospective timing are caused by two factors: the pulse rate of an internal pacemaker and the amount of attention directed to the passage of time. The results concerning the effect of attention on subjective timing have been conclusive, but the mechanisms that drive the pacemaker are still far from being understood. In two experiments, we examined the impact of two factors that in the existing literature on human time perception have been argued to affect such a pacemaker: arousal and heart rate. Experienced arousal and heart rate were varied independently by means of specific physical exercises: (a) A muscle exercise increased arousal *and* heart rate; (b) a breath-holding exercise increased arousal but decreased heart rate; and (c) in the control condition, arousal and heart rate were held constant. The results indicate that increased subjective arousal leads to higher time estimates, whereas heart rate itself has no relevant impact on time perception. The results are discussed with respect to the underlying mechanisms of prospective time perception.

**Keywords** Time perception · Heart rate · Arousal · Attention

"It will take me forever to climb these stairs!" This thought may cross our minds while we carry groceries home. When people are physically strained or stressed, the duration of events often seems to expand considerably, because physical activities seem to expand time perception (Vercruyssen, Hancock, & Mihaly, 1989; Warm, Smith, & Caldwell, 1967). Yet, despite decades of research on time perception, the exact mechanisms underlying these processes are not completely understood.

From the very first years of research on human timing, some kind of clock or pacemaker mechanism has been a crucial element of most models of time perception (see, e.g., Hoagland's, 1933, chemical clock hypothesis). The basic idea of such a mechanism is that it provides pulses or ticks (similar to those of a clock) that are used to estimate the time that has passed. These clock models have been repeatedly criticized (e.g., Staddon & Higa, 1999; Wackermann & Ehm, 2006), but some sort of pacemaker mechanism (or clock device) is still included in the majority of theoretical approaches to time perception (Grondin, 2010).

Several of the most prominent models of prospective timing[1] postulate a pacemaker mechanism to explain time perception; these include Treisman's (1963) model of the internal clock, scalar expectancy theory (Gibbon, 1977), and the attentional gate model (Zakay & Block, 1996). According to these models, basic to each time estimation process is a pacemaker that produces pulses at a certain rate. These pulses are accumulated and subsequently stored in working memory. The number of accumulated pulses within a certain interval is then compared to the number of pulses of reference durations already acquired by previous learning processes. This comparison process finally yields a duration judgment (Gibbon, Church, & Meck, 1984). Additionally, in each prospective timing model, attention to the temporal features of a time interval is essential in order to generate a duration judgment. The attentional gate model, for instance, represents this characteristic vividly with an attentional gate that can be opened or closed—depending on the amount of attention directed to the passage of time—thereby determining the number of pulses that can be accumulated. Because time perception mainly relies

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[1] Two paradigms have been established in the field of time perception: prospective and retrospective timing (Zakay, 1990). The retrospective paradigm investigates the remembered duration of an interval that has passed without its passage being explicitly noted. In contrast, in the prospective paradigm, the passage of time is explicitly the focus of attention. Therefore, in the latter paradigm, passing time is often referred to as experienced duration (Block, 1974).

on the number of accumulated pulses, it is therefore predominantly determined by the characteristics of the pacemaker and the amount of attention allocated to the timing process. Whereas a higher number of accumulated pulses is associated with longer time estimates, higher duration estimates might be caused by (a) an increase in the pacemaker rate, and/or (b) a greater amount of attention directed to the passage of time.

The effect of attention on time perception has already been the topic of numerous studies, which have mainly supported the assumption of the mentioned models that the less attention is directed to the passage of time, the shorter is the perceived duration of a certain time interval (e.g., Grondin, 2005). An established method of varying the allocation of attention is to require participants to perform a secondary (nontemporal) task simultaneously with a timing task. Kladopoulos, Hemmes, and Brown (2003), for example, asked participants to estimate time intervals while reading words aloud and compared these intervals to estimates produced without a secondary task. Time estimates were shorter when an additional task was performed, which is consistent with results of other studies (Burle & Casini, 2001; Champagne & Fortin, 2008; Chaston & Kingstone, 2004; Kojima & Matsuda, 2000; Sawyer, 2003).

In contrast, the results concerning the underlying mechanisms of the pacemaker are far less conclusive. Most pacemaker models assume that the rate of the pacemaker's pulses might be somehow influenced by the level of arousal. Indeed, some findings have indicated that increased arousal (e.g., induced by noise, sound volume, or fear) is associated with longer perceived time intervals (Burle & Casini, 2001; Grommet, Droit-Volet, Gil, Hemmes, Baker, & Brown, 2011; Miró, Cano, Espinosa-Fernández, & Buela-Casal, 2003; Noulhiane, Mella, Samson, Ragot, & Pouthas, 2007; Ozel, Larue, & Dosseville, 2004; Wearden, 2008). In addition to widely used subjective measures of arousal, heart rate is frequently reported as being a reliable physiological indicator (Coutinho & Cangelosi, 2011; Coventry & Hudson, 2001; Sforza, Jouny, & Ibanez, 2000; Thayer, 1970; Vianna & Tranel, 2006; Wulfert, Roland, Hartley, Wang, & Franco, 2005). In general, an increase in heart rate is associated with a higher level of arousal, which should in turn lead to longer duration estimates. Furthermore, heart rate might be considered a functional indicator of the pacemaker because it produces pulses that might serve perfectly as a basis for time estimation.

Yet the findings concerning the impact of heart rate on time perception are, unfortunately, far from conclusive. Some researchers have found no impact of heart rate on time estimation, but others have obtained meaningful correlations. Carrasco, Redolat, and Simón (1998) examined time estimates by smokers and nonsmokers, who differed in heart rates but not in their time estimates. Other researchers have also questioned a relationship between time estimates and heart rate (Ochberg, Pollack, & Meyer, 1964) or have postulated only a minor or insignificant role for heart rate in time perception (Surwillo, 1982, p.105). In contrast, Hawkes, Joy, and Evans (1962) reported correlations up to .44 between heart rate and time estimates, by using different kinds of drugs to change the physiological parameters of their participants. Cahoon (1969) varied heart rate by threatening participants with electric shocks (which they did not, in fact, receive) and concluded that the participants were probably "responding to the perception of [their] own heart beat in establishing a subjective time rate" (p. 266). Also, Jamin, Joulia, Fontanari, Bonnon, Ulmer and Crémieux (2004) investigated the effect of heart rate on time estimations among diving, cycling, and resting athletes. In two experiments, Jamin et al. obtained considerable correlations between time estimates and heart rates.

In sum, subjective arousal ratings seem to be associated with differences in time perception, but the relationship between heart rate and time estimation is still unresolved. There are two possible explanations for these findings: (1) Heart rate is not a reliable indicator of arousal (and, therefore, not a good predictor of human time perception), and (2) heart rate per se has no distinct impact on time perception. One way to examine these explanations would be to dissociate heart rate from arousal during a timing task by using an innovative approach: taking advantage of the *diving reflex*. The diving reflex is a well-documented autonomous physiological mechanism causing a reduction in heart rate for persons immersed in water or holding their breath (Folgering, Wijnheymer, & Geeraedts, 1983; Gooden, 1994; Ross & Steptoe, 1980; Sterba & Lundgren, 1985). This mechanism might function as a way to avoid an undersupply of oxygen by reducing the consumption of the already dissolved blood oxygen. This reflex enables the conductance of a potentially arousing task while keeping the heart rate relatively low.

In the present studies, we varied heart rate and subjective arousal independently. In particular, we used two potentially arousing physical exercises to increase participants' arousal levels: a muscular exercise and a breath-holding exercise. However, participants in the two exercises were expected to differ in their mean heart rates, due to the diving reflex (induced in the breath-holding exercise). A control condition was implemented to establish baselines for heart rate and subjective arousal.

We empirically tested two competing hypotheses: The *heart-rate hypothesis* postulates that heart rate influences the pacemaker directly. If this is the case, longer perceived time intervals should be obtained in the muscular exercise condition (inducing a high heart rate) than in the breath-holding and control conditions (inducing lower heart rates). In contrast, the *subjective-arousal hypothesis* postulates that subjective arousal determines time perception. If this hypothesis holds true, longer perceived time intervals should be obtained in both the muscular exercise *and* the breath-holding conditions than in the control condition, because both physical-exercise conditions should induce high subjective arousal. To test the two competing hypotheses, we conducted two experiments using different measures of time perception: time estimation (Exp. 1) and time production (Exp. 2).

## Experiment 1

In the first experiment, we compared participants' time estimates in three experimental conditions: (1) a muscular exercise (ME) condition, which should induce subjective arousal *and* increase heart rate; (2) a breath-holding (BH) condition, which was implemented to induce subjective arousal as well, but at the same time to decrease heart rate slightly (due to the diving reflex); and (3) a control condition, which was intended to provide baselines for subjective arousal and heart rate. In order to test the heart-rate hypothesis against the subjective-arousal hypothesis, we compared time estimates in the three conditions according to their fit to either the heart-rate or the arousal variations across the conditions.

### Method

#### *Participants*

A group of 30 undergraduates at Chemnitz University of Technology (20 female, 10 male; mean age: 25.5 years, *SD* = 6.5) participated in the experiment and received course credit to satisfy an academic requirement.

#### *Material*

The stimuli used for the time estimation task were 14 simple symbolic figures, easily distinguishable by shape (see Fig. 1). The figures were presented in random order,[2] each for 8 s. The actual presentation duration was concealed and—as the data show—was not noticed by the participants. The interstimulus intervals were 4, 5, or 6 s (randomly assigned), in order to avoid the appearance of any kind of constant pace, which might have affected time estimation. The experiment was programmed by means of E-Prime 2.0 software (Psychology Software Tools, 2007) and run under a Windows XP environment with 15-in. monitors. Heart rate (measured in beats per minute, or bpm) was collected by use of a Mind Media BV instrument (NeXus-16) and BioTrace+ software (Mind Media BV, 2004).

#### *Procedure*

All participants were tested individually. Upon arrival, they were informed that they were to perform different exercises while watching series of stimuli appearing consecutively on a computer screen, and that they would be asked to judge the presentation duration of each of the stimuli immediately after each exercise. The participants were asked to place all timepieces out of sight and were equipped with electrocardiogram electrodes for heart-rate measurements. They were explicitly asked to avoid counting seconds because of the reported effects of such strategies on time judgments (e.g., Clément & Droit-Volet, 2006; Grondin, Meilleur-Wells, & Lachance, 1999; Grondin, Ouellet, & Roussel, 2004; Hicks & Allen, 1979; Rattat & Droit-Volet, 2012). Initially, all participants were familiarized with the three experimental conditions in a short training phase. For the ME condition, participants had to get in a position in which they leaned against a wall with a 90-deg angle between their thighs and shanks. Their view was directed at a computer screen, where they saw the stimulus presentation. For the BH exercise, participants (sitting in front of the computer screen) were asked to hold their breath while following the stimulus presentation. The impacts of these two physical exercises on the relevant measures were highly dependent on the individual physical fitness and capabilities of the participants. Because a standardized 2-min exercise duration would affect each participant very differently, the participants were asked to hold the position (and their breath, respectively) as long as possible before terminating these exercises by themselves. However, in the control condition, participants were asked just to watch the stimulus presentation on the screen while they were seated in front of it. This condition was terminated automatically after about 2 min (which meant after nine stimuli) in order to create experimental conditions with preferably similar durations. In a pretest, most participants terminated the ME and BH exercises within 2 min. During each condition, the participants watched the presentation of the stimuli on a computer screen. Immediately after the termination of the exercises, participants were asked to estimate the presentation duration of each previously seen stimulus by typing in the answer via the keyboard. To avoid sequential effects on the estimates, stimuli were always presented in random order. Participants were explicitly informed that each stimulus had been presented for between 1 and 60 s. Subsequently, the participants' subjective arousal was obtained by asking them to evaluate the intensity of subjective strain caused by each condition, on a scale from 0 (*not straining*) to 9 (*very straining*). We gave precedence to this measure because alternative terms such as

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[2] The symbolic figures were presented in random order, which should per se control for any potential impact of the kind of figure on the time estimates by distributing figures randomly in each condition. However, to check for order effects, we ran an additional analysis of variance that revealed no differences in the time estimates for specific figures, F(13, 166) = 1.01, p = .441.

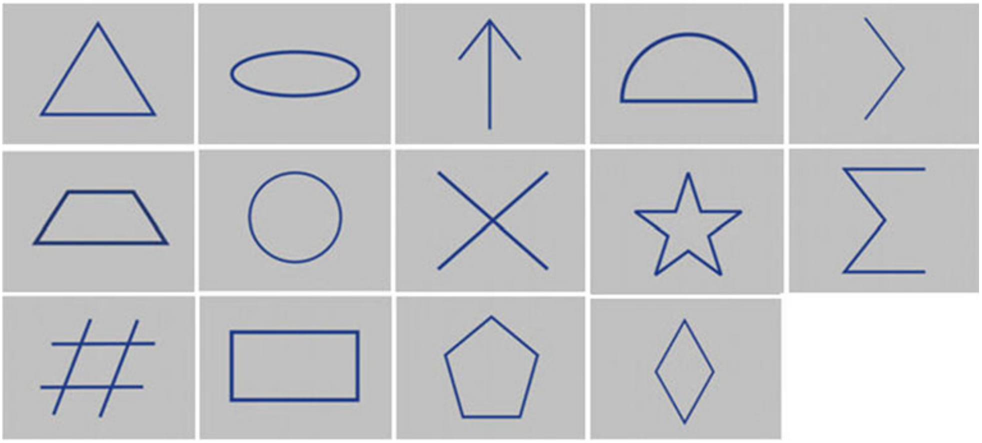

**Fig. 1** The 14 simple symbolic figures used for the time estimation task

"activation" and "arousal" might have been misunderstood in their German translation, and in this context, respectively. All participants completed each of the three conditions twice, whereby the order of the conditions was randomized with the restrictions that (a) no exercise appeared twice in succession and (b) BH never directly followed ME. This was done to enable participants to recover their breath between the exercises. Thus, the whole experimental procedure took about 30–40 min, depending on the individual physical capabilities of the participants.

### *Data analysis*

To deal with individual differences in physical capability, and therefore to ensure the maximum impact of the exercises on each participant individually, the arousal and heart-rate measures were analyzed for the last 8 s (the last stimulus presentation) of each exercise. Consistent with this procedure, only time estimates of the last stimulus seen immediately before termination of the exercises were analyzed. For reliability reasons, the measures of the two trials for each of the three conditions were averaged.

Although the predictions of the heart-rate hypothesis and the subjective-arousal hypothesis could be roughly specified in advance, a more exact test of the two hypotheses would take into account the actual individual variations in heart rate and subjective arousal across the three tasks that each individual had to perform. Therefore, for each participant, we calculated the fit between that individual's variations in heart rate and subjective arousal, on the one hand, and that individual's duration judgments, on the other. The fits were thereby calculated as the correlations ($r$) across the three tasks. Thus, each individual contributed two fit measures to the analysis, one for the relationship between heart rate and duration judgments, and the other for the relationship between subjective arousal and duration judgments. These fit measures were then subjected to inferential statistics. Note that this procedure is nothing but a repeated measures contrast analysis (Rosenthal, Rosnow, & Rubin, 2000, pp. 128–130), in which the mean fit is tested against the null hypothesis of 0 (no fit) using a one-sample $t$ test. We used the same procedure to check whether the experimental manipulations had worked. Here, for every participant we calculated the correlation between the a-priori-specified contrasts (the expected variations) and the actual variations in heart rate and subjective arousal, respectively, as measures of fit. We will always report the average fit $(\overline{r})$, and as a measure of effect size that expresses the overall fit of the hypotheses with the data, Hedges's $g$ will be reported throughout (Rosenthal et al., 2000; Sedlmeier & Renkewitz, 2007).[3]

## Results

### *Experimental manipulation effects*

We first analyzed whether the different experimental conditions affected subjective arousal and heart rate as initially expected. As is shown in Fig. 2, we found a substantially increased mean heart rate in the ME condition relative to the BH and control conditions, and just a small difference in heart rate between the BH and control conditions. For the ME condition, we expected heart rate to increase, whereas it was not expected to differ much in the other two conditions. To test these expectations, we assigned the following contrast weights to the conditions: −1 to control, −1 to BH, and 2 to ME. The results of the contrast analysis also clearly indicated that our experimental manipulation concerning variations in heart rate worked ($\overline{r} = .83$, $p < .001$, $g = 5.17$). The rather high mean heart rate in the present sample (see the 86.2 bpm in the control condition) seems to have been due to a significantly

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[3] Note that although the average fit $(\overline{r})$ gives information about the size of the fit, it does not take into account the variation of the individual fit indices (r). Yet the size of this variation (small or large) matters, and this information is captured in standard effect sizes such as g.

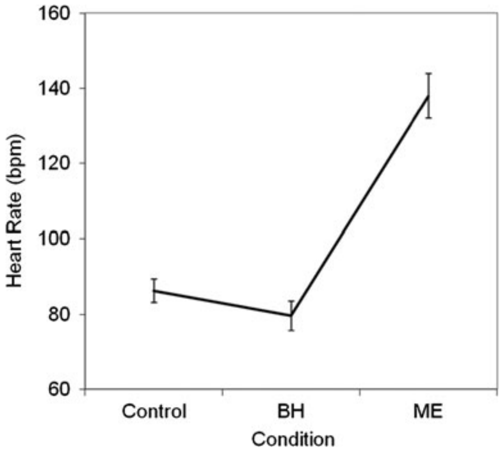

**Fig. 2** Mean heart rates, in beats per minute (bpm), in the experimental conditions of Experiment 1. The error bars represent standard errors. BH, breath-holding condition; ME, muscular exercise condition

higher heart rate in female participants (66 % of all participants in our sample), $t(28) = 3.30$, $p = .002$, $g = 1.30$, with the difference averaging 17 bpm. Note that higher heart rates for females seem to be a common finding in the literature (e.g., Mendonca, Heffernan, Rossow, Guerra, Pereira, & Fernhall, 2010; Wallin, Hart, Wehrwein, Charkoudian, & Joyner, 2010; Whited & Larkin, 2009).

As we expected, participants judged both physical conditions (BH and ME) to be substantially more arousing than the control condition (see Fig. 3).To test our expectations, we assigned contrast weights of −2 to the control condition and 1 to both the BH and ME conditions. The contrast analysis supported the expected changes in subjective arousal, $\overline{r} = .85$, $p < .001$, $g = 2.17$.

### *Time estimates*

The actual presentation duration of 8 s for each stimulus was overestimated in all conditions. Nevertheless, as is shown in Fig. 4, time estimates were obviously much higher in both physical conditions (ME and BH) than in the control condition.

The heart-rate hypothesis assumes that heart rate influences the pacemaker, and therefore time estimates are expected to be higher with increased heart rate. Thus, time estimates should have been highest in the ME condition and considerably lower in the BH and control conditions. To test this hypothesis, each participant's heart rates in the three conditions were correlated with that participant's time estimates, resulting in individual fit measures (correlations) between variations in heart rate and the respective variations in time estimates over the experimental conditions. The averaged correlation was subjected to a one-sample *t* test, and we found no support for the hypothesis that heart rate affects time estimates, $\overline{r} = -.01$, $p = .909$, $g = -0.02$.

The subjective-arousal hypothesis holds that arousal determines time perception by accelerating the pacemaker. Recall that time estimates were expected to be generally higher in the arousing BH and ME conditions, as compared to the control condition. Nonetheless, to test the hypothesis in a more precise way, we again calculated the fit between each participant's arousal ratings and that participant's time estimates as the correlation of these measures over the three tasks. The results of the contrast analysis supported the subjective-arousal hypothesis: $\overline{r} = .19$, $p = .045$, $g = 0.38$.

To compare the two hypotheses directly, we calculated the difference in the fits of the heart-rate hypothesis (correlation between heart rates and time estimates) and of the subjective-arousal hypothesis (correlation between arousal ratings and time estimates) for each participant. These differences were then subjected to a one-sample *t* test. The

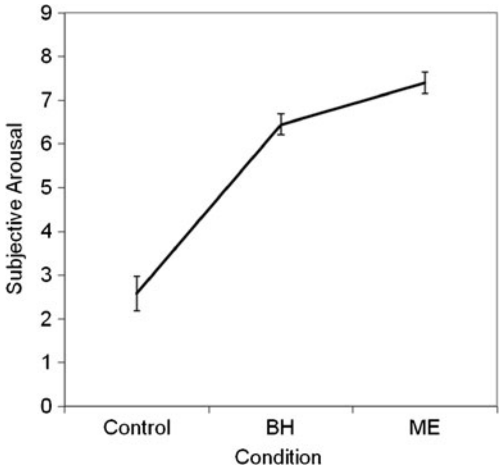

**Fig. 3** Mean subjective arousal on a scale from 0 (*not straining*) to 9 (*very straining*) in the experimental conditions of Experiment 1. The error bars represent standard errors. BH, breath-holding condition; ME, muscular exercise condition

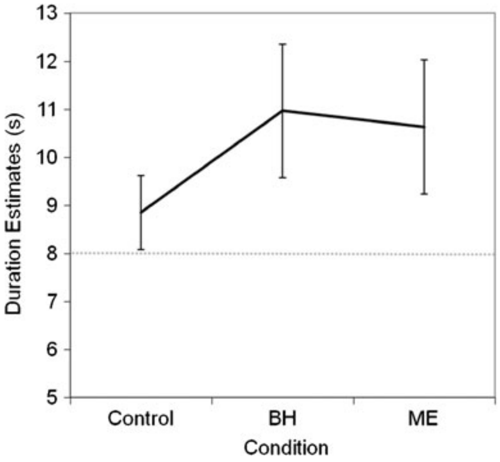

**Fig. 4** Mean duration estimates, in seconds, in the experimental conditions of Experiment 1. The error bars represent standard errors. The dotted gray line illustrates the actual presentation duration of 8 s. BH, breath-holding condition; ME, muscular exercise condition

results indicated that the fit for the subjective-arousal hypothesis was clearly better than that for the heart-rate hypothesis ($\bar{r}_{\mathrm{diff}} = -.20$, $p = .026$, $g = -0.43$).

### Discussion

The results of Experiment 1 suggest that time perception is affected by arousal in general rather than by heart rate specifically, thus contradicting the heart-rate hypothesis. Heart rate—whether as an indicator of arousal or as a potential physiological correlate of the pacemaker—does not seem to be a sufficient predictor for time perception, although this has been suggested in previous studies (e.g., Cahoon, 1969; Hawkes et al., 1962; Jamin et al., 2004). The second hypothesis focused on subjective arousal as a factor in time perception. The subjective-arousal hypothesis was supported by our results, with subjective arousal turning out to be a good predictor of time estimates. Thus, our results conform to the predictions of scalar expectancy theory (SET) and the attentional gate model (AGM). Nevertheless, to understand the underlying mechanisms of time perception better, we have to find out how, exactly, arousal affects time estimation. According to SET and the AGM, arousal determines time perception by influencing the speed of a pacemaker. In this way, higher arousal is supposed to accelerate the rate of the pacemaker and, therefore, to increase the number of accumulated pulses within a certain time span. This, in turn, causes higher estimates of the particular time interval. However, both SET and the AGM also offer an alternative explanation: Physical effort (and thus arousal) might increase participants' attention to temporal information. This effect could be equally expected in both of our Experiment 1 tasks, because the anticipated end of the straining exercises becomes more salient over the course of the exercise. Increased attention to timing might also cause a higher number of accumulated pulses within the same time interval, and this in turn may lead to higher time estimates. Indeed, apart from the research on time perception, a number of findings have indicated an interaction of arousal and attention. Several researchers have reported variations in the allocation of visual attention due to induced differences in arousal (De Houwer & Tibboel, 2010; Fernandes, Koji, Dixon, & Aquino, 2011; McConnell & Shore, 2010; Verbruggen & De Houwer, 2007). However, the question is now whether we can determine whether increased arousal or a stronger focus on timing caused the differences in time perception that we obtained.

## Experiment 2

With the second experiment, we pursued two main goals. First, we attempted to replicate the results of Experiment 1, using a different method of measurement (time production) to enhance the generality of the findings. Second, we attempted to test a potential alternative explanation of the results obtained in Experiment 1, which we term the *arousal-attention hypothesis*: Arousal might not have influenced the rate of the pacemaker, but instead increased attention to the temporal features of the task, and therefore increased time estimates. Time perception was again analyzed using the same exercises as in Experiment 1: an ME and a BH task. Again, a control condition was intended to provide baselines for subjective arousal and heart rate. To examine the arousal-attention hypothesis, we asked participants to assess the amount of attention that they dedicated to the timing task. Moreover, to examine the validity of this assessment of subjective attention, we varied attention allocation by implementing a secondary (nontemporal) task to be performed while performing the different exercises.

Because we used a different method of measuring time perception in Experiment 2, a few remarks might be warranted to clarify the differences in the expected findings, as compared to Experiment 1. According to Zakay and Block (1996), whenever the AGM predicts *longer* verbal time estimates of a certain interval, it also predicts *shorter* produced intervals. How is this inverse relationship between verbal estimates and time production to be explained? First, for verbal estimates, the number of accumulated pulses is compared with a reference memory, and the more pulses that are counted, the longer the respective time span $x$ is estimated to be. To produce intervals, the time judgment is obtained in a slightly different way: The participant in such a task is required to indicate the beginning and the end of a time span with a predetermined duration (e.g., 8 s, as in the present experiment) by pressing a start–stop button. The production stops when the number of accumulated pulses reaches the number for the particular time span stored in reference memory. Hence, given the same actual time span $x$, when the pacemaker is accelerated, the required number of pulses will be accumulated in a shorter period of time, and therefore the interval will be terminated sooner. Analogously to the prolonged time estimates in Experiment 1, we therefore expected shorter produced intervals in the physical conditions (ME and BH) as compared to the control condition.

To validate the findings of Experiment 1, we kept the previous two hypotheses and adapted them to the production method. The heart-rate hypothesis in Experiment 2 predicts shorter time productions with higher heart rates. We therefore expected the time intervals produced in the ME condition to be shorter than those produced in both the BH and the control condition. According to the subjective-arousal hypothesis, interval productions should be shorter in *both* arousing exercise conditions (BH and ME) than in the control condition. The newly added arousal-attention hypothesis predicts that arousal does not have a strong impact on the pacemaker, but rather increases the amount of attention to the passage of time. Note that the prediction of this hypothesis concerning interval productions is identical to that of the subjective-arousal hypothesis, but the two hypotheses can be tested against each other by inspecting the allocation of attention. If the arousal-attention hypothesis holds, we should see higher ratings of attention to the timing task in both arousing conditions (BH and ME) than in the control condition. The inclusion of a secondary task served as a manipulation check: If participants had to deal with a secondary task, they should be aware of their diminished attention to the timing task, in all conditions.

## Method

### *Participants*

A group of 30 undergraduates at Chemnitz University of Technology (23 female, seven male; mean age: 21.7 years, *SD* = 2.7) participated in the experiment and received course credit.

### *Material*

The 14 symbolic figures from Experiment 1 were used for the secondary nontemporal task. The figures were presented for 2–6 s each with an interstimulus interval of 4, 5, or 6 s. The durations of the stimulus presentations and the interstimulus interval were selected randomly. The same technical devices and software were used for data collection as in Experiment 1.

### *Procedure*

The participants were tested individually. Upon arrival, they were informed that they would be required to perform different physical exercises while successively producing time intervals of 8 s by repeatedly pressing the space bar of a computer keyboard. The fixed 8-s time intervals enabled an elegant way to directly compare the results of Experiments 1 and 2 and to avoid further variance due to differences in the actual durations. Furthermore, participants were told that they would be required to watch a stimulus presentation during some of the exercises (the secondary, nontemporal-task conditions) and that they were to answer some questions about these stimuli afterward. Participants were equipped with electrodes measuring heart rate and were asked not to count seconds (as in Exp. 1). All timepieces were placed out of sight. A short training in the three conditions (ME, BH, and control) was conducted to familiarize the participants with the procedure. Again, participants were encouraged to stay in the ME position for as long as possible, and to hold their breath for as long as they were able to in the BH condition. Thus, in both physical-exercise conditions, each participant was required to terminate the exercises her- or himself. The presentation in the control condition was terminated automatically after 2 min, as in Experiment 1.

Participants had to take part in each of the three conditions twice, once with and once without the secondary task. To avoid sequential effects, the tasks were assigned in random order. As in Experiment 1, no exercise appeared twice in succession, and BH never directly followed ME.

Immediately after the termination of each exercise, participants were again required to assess their subjective arousal on a scale from 0 (*not straining*) to 9 (*very straining*), as well as the amount of attention that they had directed to the timing task on a scale from 0 (*no attention*) to 9 (*much attention*). Questions about the frequencies and features of the distraction stimuli were asked in order to foster compliance with the experimental requirements and were not included in the data analyses. The whole experimental procedure took about 20 to 30 min, depending on the individual physical capabilities of the participants.

### *Data analysis*

As in Experiment 1, all physiological data were analyzed for the last 8 s in each experimental condition. Likewise, the last time intervals produced prior to the termination of each exercise were selected for the statistical analyses. Repeated measures contrast analyses were conducted analogously to Experiment 1, separately for manipulation checks and for time productions with and without a secondary task.

## Results

### *Experimental manipulation effects*

We first report whether heart rate and the ratings of subjective arousal varied in the three conditions as intended, as well as whether the secondary task reduced attention to the timing task. As in Experiment 1, we found an increased mean heart rate in the ME condition, whereas relatively low values were found in the BH and control conditions (Fig. 5). This was the case independent of whether participants performed the secondary task. Again, we assigned contrast weights of −1 to both the control and BH conditions, and a weight of 2 to the ME condition. The contrast analyses indicated in both secondary-task conditions (with and without a secondary task) that heart rate varied between the exercise conditions as expected (without secondary task, $\overline{r} = .92$, $p < .001$, $g = 3.43$; with secondary task, $\overline{r} = .90$, $p < .001$, $g = 3.65$). Because we had no specific hypothesis on heart rate differing in the secondary-task conditions, we calculated a repeated measures analysis of variance (ANOVA) to check for differences. The performance of the secondary task had no effect on heart rates, $F(1, 29) = 0.72$, $p = .402$, $g = 0.16$. Again,

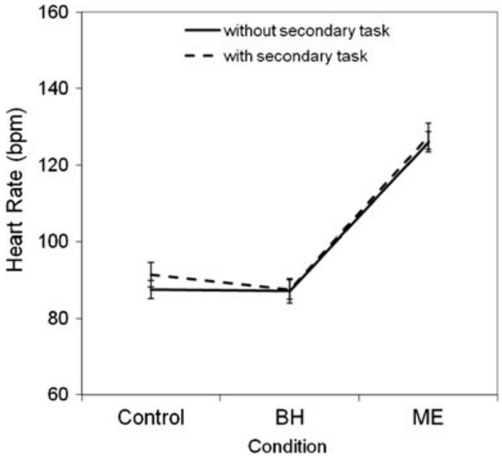

**Fig. 5** Mean heart rates, in beats per minute (bpm), in the experimental conditions of Experiment 2. The error bars represent standard errors. BH, breath-holding condition; ME, muscular exercise condition

the rather high mean heart rates in the control condition seem to have been caused by the significantly higher heart rates of female participants [without secondary task, $t(28) = 2.90$, $p = .008$, $g = 1.25$; with secondary task, $t(28) = 2.50$, $p = .019$, $g = 1.08$], who made up 76 % of all participants in this experiment.

Similar to the participants in Experiment 1, the participants here judged the ME and BH conditions to be much more arousing than the control condition (see Fig. 6). The performance of the secondary task seems to have had no effect on the subjective arousal appraisals in the physical-exercise conditions. However, in the control condition we found a noteworthy difference, with higher ratings in the secondary-task condition. To test whether the subjective arousal measures followed our expectations, we again calculated contrast analyses, assigning contrast weights of −2 to the control condition and of 1 to both the ME and BH conditions (separately for the secondary-task conditions). Both analyses clearly supported our assumptions (without secondary task, $\overline{r} = .92$, $p < .001$, $g = 4.49$; with secondary task, $\overline{r} = .92$, $p < .001$, $g = 7.01$). Because of the disproportionate difference in the control condition, we calculated separate paired two-sample *t* tests instead of a repeated measures ANOVA to examine the effect of the secondary task on the subjective arousal judgments. Whereas subjective arousal was rated considerably higher in the secondary-task condition for the control condition, $t(29) = 2.70$, $p = .011$, $g = 0.49$, no relevant differences occurred for the BH condition, $t(29) = 0.12$, $p = .902$, $g = 0.02$, or the ME condition, $t(29) = 0.62$, $p = .541$, $g = 0.11$.

Whether participants completed a secondary task seems to have had an effect on their subjective attention to timing. As is depicted in Fig. 7, we found a systematic decline in attention to the timing task if a secondary task was performed. To examine these differences, we conducted a repeated measures ANOVA, which indicated that the performance of the secondary task reduced attention to the timing task, $F(1, 29) = 6.90$, $p = .014$, $g = 0.96$.

## Time productions

Participants were asked to produce intervals of 8 s by pressing the space bar of a computer keyboard. Consistent with the results for the estimation task in Experiment 1, the intervals produced were shorter than 8 s in all conditions except the control condition with the secondary task. Figure 8 illustrates that the produced intervals were consistently longer when participants had to perform a secondary task. Corresponding to the results of Experiment 1, shorter produced intervals occurred in both physical-exercise conditions (ME and BH)

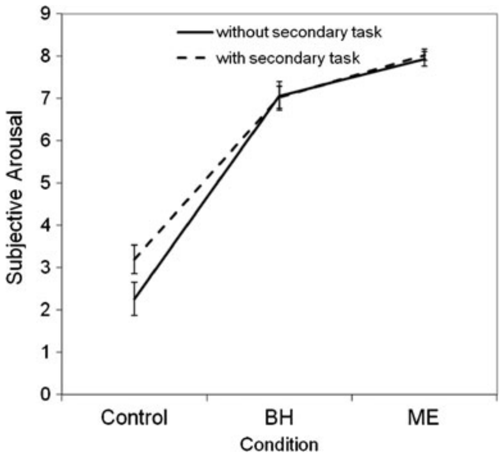

**Fig. 6** Mean subjective arousal on a scale from 0 (*not straining*) to 9 (*very straining*) in the experimental conditions of Experiment 2. The error bars represent standard errors. BH, breath-holding condition; ME, muscular exercise condition

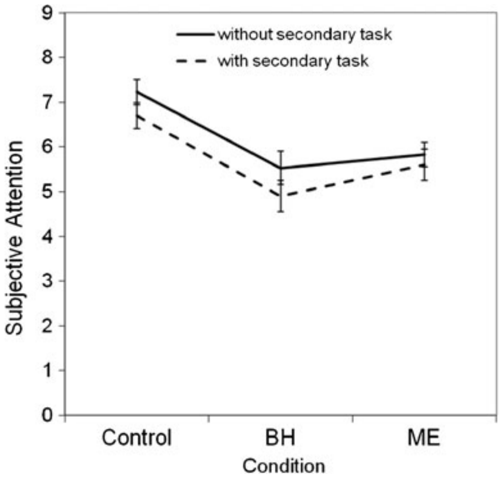

**Fig. 7** Mean subjective attention to the timing task on a scale from 0 (*no attention*) to 9 (*much attention*) in the experimental conditions of Experiment 2. The error bars represent standard errors. BH, breath-holding condition; ME, muscular exercise condition

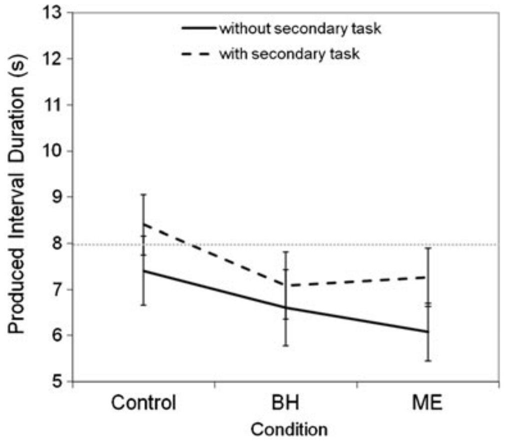

**Fig. 8** Mean produced durations, in seconds, in the experimental conditions of Experiment 2. The error bars represent standard errors. The dotted gray line marks the target duration of 8 s. BH, breath-holding condition; ME, muscular exercise condition

than in the control condition, independent of the secondary task.

According to the heart-rate hypothesis, the mean time productions should be shorter in the ME condition than in the control and BH conditions (because of variations in mean heart rates). As in Experiment 1, fit indices for heart rate were generated by correlating individual heart rates and the time productions for each participant over the experimental conditions (separately for the two secondary-task conditions). Again, we found no support for the hypothesis that heart rate affects time perception (without secondary task, $\overline{r} = .09$, $p = .470$, $g = 0.13$; with secondary task, $\overline{r} = .20$, $p = .100$, $g = 0.31$).

Following the subjective-arousal hypothesis, time productions should be shorter in the more arousing conditions (BH and ME) than in the control condition. To test this hypothesis, we calculated the fit indices accordingly by correlating individual arousal judgments and the time productions. The results of both contrast analyses support the subjective-arousal hypothesis (without secondary task, $\overline{r} = .36$, $p = .010$, $g = 0.50$; with secondary task, $\overline{r} = .44$, $p = .001$, $g = 0.70$).

As in Experiment 1, we also compared the two hypotheses by calculating the difference in the correlations between heart rate and the time productions and between arousal ratings and the time productions. Finally, this measurement of difference between the two hypotheses was subjected to a one-sample *t* test. The results indicated that the fit for the arousal hypothesis was substantially better than that for the heart-rate hypothesis (without secondary task, $\overline{r}_{diff} = .27$, $p = .049$, $g = 0.37$; with secondary task, $\overline{r}_{diff} = .24$, $p = .016$, $g = 0.47$).

According to the arousal-attention hypothesis, higher arousal should increase the amount of attention to the temporal features of the task, and therefore, higher attention ratings for the arousing conditions (BH and ME) than for the control condition would be expected. However, when we compared the three experimental conditions, subjective attention to timing was highest in the control condition, whereas the attention judgments in the BH and ME conditions were substantially lower (see Fig. 7). In fact, the attention judgments revealed the opposite pattern, a clear argument against the arousal-attention hypothesis.

Because there was an effect of the secondary task on subjective attention to timing, we further analyzed the effect of attention on time production. As can be seen in Fig. 8, a clear difference appeared in the mean time productions, depending on whether participants performed a secondary task. Because earlier studies had proposed that a reduction of attention to timing would lead to a shorter time perception, we expected longer time productions for the conditions with a secondary task. We examined this effect by calculating paired two-sample *t* tests separately for each condition. Indeed, the time productions were longer with the secondary task, although the difference in the BH condition did not reach significance [control condition, $t(29) = 2.42$, $p = .022$, $g = 0.44$; BH condition, $t(29) = 1.51$, $p = .141$, $g = 0.28$; ME condition, $t(29) = 3.16$, $p = .004$, $g = 0.58$].

## Discussion

In Experiment 2, the main results of Experiment 1 were replicated. At first glance, Figs. 4 and 8 do not look very similar. However, taking the inverse relationship between the methods of time estimation and time production into account, we obtained nearly the same result pattern of time perception over the three experimental conditions. The results of both experiments do not support the assumption that heart rate directly affects the pacemaker (heart-rate hypothesis). Instead, subjective arousal determines human time perception much better (subjective-arousal hypothesis).

The results of Experiment 1 raised the question of whether the higher time estimates in the arousing conditions (BH and ME) were caused by an acceleration of the pacemaker as a result of induced arousal or by increased attention to the temporal features of the task (arousal-attention hypothesis). To answer this question, we first verified that participants were sensitive to their allocation of attention to timing by examining the attention judgments when attention was distracted from timing by a secondary task. As expected, participants judged their attention to timing to be reduced in the secondary-task conditions. However, independent of whether the secondary task was to be performed, subjective attention was rated as being considerably lower in the physical-exercise conditions than in the control condition. This result clearly contradicts the arousal-attention hypothesis. Rather, the physical exercises seem to have distracted attention from timing.

When we consider the results in the secondary-task conditions, both factors, arousal and attention, seem to have had an effect on time perception as postulated by SET and the AGM: On the one hand, in the arousal-inducing conditions (BH and ME), participants produced shorter time intervals, possibly induced by an acceleration of the pacemaker. On the other hand, in the secondary-task conditions we obtained longer time productions, conceivably because participants' attention to timing was reduced. Considering the common effects of arousal and attention sheds light on an interesting point: On the basis of the (lower) attention ratings in both physical-exercise conditions, we would have expected longer time productions than in the control condition; in fact, they were shorter. Because attention to timing was reduced in the physical conditions *and* subjective arousal was increased at the same time, the results suggest—at least in our experimental setting—that the impact of arousal on time perception is stronger than the effect of attention allocation.

## General discussion

The aim of this study was to investigate heart rate and subjective arousal as potential underlying mechanisms for a pacemaker that has been postulated in prominent models of time perception. In two experiments, we independently manipulated heart rate and subjective arousal, and additionally varied attention to timing by including a secondary (nontemporal) task in Experiment 2. Time perception was recorded by means of time estimation in Experiment 1 and of time production in Experiment 2.

The main result of our study was that heart rate is not a good predictor of time perception, and therefore it seems not to affect the pacemaker directly. This conclusion is supported by the data from both experiments, with two different samples and two different measures of time perception. Thus, the present results corroborate the position that heart rate does not play a prominent role in the timing process. Our results provide an explanation for the divergent empirical findings in earlier research on human time perception concerning the relationship between heart rate and arousal. Although heart rate is a widely used arousal indicator, there is evidence that under some circumstances the covariation with other physiological indicators, such as skin conductance and respiration rate, seems to disappear (Taylor & Epstein, 1967). Similar findings have been reported for the correlation between heart rate and subjective arousal (Balteş, Avram, Miclea, & Miu, 2011; Bensafi, Rouby, Farget, Bertrand, Vigouroux, & Holley, 2002; Lang, Greenwald, Bradley, & Hamm, 1993; Schäfer & Sedlmeier, 2011; Van der Zwaag, Westerink, & Van den Broek, 2011). Further doubts on the reliability of heart rate as an indicator of arousal arise from studies on the conscious controllability of heart rate (Carroll & Whellock, 1980; De Pascalis, Palumbo, & Ronchitelli, 1991) and on autonomous changes of heart rate, such as the diving reflex (Folgering et al., 1983; Gooden, 1994; Ross & Steptoe, 1980; Sterba & Lundgren, 1985). In sum, it seems that heart rate under some circumstances is inconsistent with the arousal concept. A main novel contribution of the present research is the distinction between heart rate and arousal in an experimental setting. As the results show, heart rate does not determine time perception in general, although there are conditions under which it covaries with time judgments.

In contrast to heart rate, subjective arousal predicted time perception in both experiments quite well, which is consistent with the findings from earlier research. Because of the relatively broad concept of arousal, involving numerous correlates, structures, and processes, our results are not yet sufficient to further narrow down the basis of the pacemaker. Both SET and the AGM postulate arousal as being the determinant of the pacemaker, and much research has investigated the physiological and neurological structures underlying these mechanisms. The current research on a pacemaker has headed in different directions. Different time scales might use different clock mechanisms: That is, time judgments over months, days, seconds, and milliseconds seem to rely on mostly different physiologies (Buonomano, 2007). Moreover, even for time intervals from seconds to minutes, various neuronal structures seem to be involved instead of one single "clock." For example, the striatal beat frequency model suggests that various structures of the cortex, the thalamus, and the striatum are responsible for the pace underlying time perception (Matell & Meck, 2000).

The role of attention in timing was examined in Experiment 2. Distracting attention from the timing task significantly increased time productions, as expected. Nevertheless, time productions decreased in the arousal-inducing conditions, shedding light on the relationship between the two main determinants of time perception according to SET and the AGM: the pacemaker and attention. Each of these determinants has a strong and model-consistent impact on time perception, but it seems that arousal is more effective in modulating time judgments than attention. Of course, this is only a first speculation about the relationship between attention and arousal within the timing process. Given previous findings about the impact of arousal on attention (De Houwer & Tibboel, 2010; Fernandes et al., 2011; McConnell & Shore, 2010; Verbruggen & De Houwer, 2007), and vice versa (De Bourdeaudhuij, Crombez, Deforche, Vinaimont, Debode and Bouckaert 2002), it could be worthwhile to take a closer look at this topic in the context of time perception.

Our results seem to confirm the predictions of SET and the AGM by revealing effects of both arousal and attention on time perception, which are not predicted by pacemaker-free models (see Staddon & Higa, 1999; Wackermann & Ehm, 2006). We therefore agree with the assumption that a pacemaker mechanism is involved in time perception, but we suggest that the existing models need to be enhanced and improved with regard to the nature of the relatedness and possible interactions of the two main timing determinates, arousal and attention. The results of this study might be used as a first step in that direction.

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