# Effects of motion on time perception☆

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ABSTRACT

To investigate the effect of motion on time perception, participants were asked to perform either a temporal discrimination task or a temporal generalization task while running or standing still on a treadmill. In the temporal discrimination (bisection) task, 10 participants were exposed to two anchor stimuli, a 300-ms Short tone and a 700-ms Long tone, and then classified intermediate durations in terms of their similarity to the anchors. In the temporal generalization task, 10 other participants were exposed to a standard duration (500 ms) and then judged whether or not a series of comparison-durations, ranging from 300 ms to 700 ms, had the same duration as the standard. The results showed that in the temporal bisection task the participants produced more "Long" responses under the dual-task condition (temporal judgments + running) than under the single-task condition (temporal judgments only). In the temporal generalization task, accuracy in the temporal judgments was lower in the dual-task condition than the single-task condition. These results are discussed in the light of dual-task paradigm and of the Scalar Expectancy Theory (SET).

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## 1. Introduction

To behave adaptively, animals and humans need to be sensitive to the temporal properties of the environment and the temporal properties of their behavior (Grondin, 2010; Michon, 1993). The study of the ability to discriminate the order and duration of events (time perception), to differentiate the temporal properties of actions (temporal differentiation), and, more generally, to regulate behavior on the basis of the temporal attributes of the environment is called *interval timing*, or simply *timing* (see Richelle and Lejeune, 1980; Wearden, 2008).

Timing has been usually studied by means of four basic tasks: (1) verbal estimation; (2) production; (3) reproduction and (4) discrimination. In verbal estimation tasks, the participant is asked to estimate verbally the duration of a standard stimulus. In production tasks, the participant is asked to produce a standard duration specified verbally by the experimenter (e.g., "Press a button for 10 seconds"). In reproduction tasks, the participant is asked to reproduce a standard duration presented by experimenter. And finally, in discrimination tasks (the most common are temporal bisection and temporal generalization), a stimulus is presented by the experimenter and the participant is asked to classify it as more similar to a Short or to a Long standard (temporal bisection), or to classify it as Equal to or Different from a standard (temporal generalization). We refer to the subject's response generically as "judgment" and the duration the subject is asked to judge generically as "standard" (Bindra and Wakesberg, 1956).

To account for the results obtained in timing tasks, researchers have use a variety of concepts (e.g., under and overestimation, subjective and objective time units, speed of internal and external clocks, etc.), but these concepts have not always been used in clear and consistent ways (see Bindra and Wakesberg, 1956). To avoid confusion, henceforth we adopt the conceptual framework of the Scalar Expectancy Theory (SET). SET is an information-processing model that postulates an internal clock with three components: a pacemaker–accumulator unit, a memory store, and a comparator/decision component. At the onset of the standard stimulus, the pacemaker starts to generate pulses at a high rate, which pulses are then added in the accumulator. When the standard ends, the number of pulses in the accumulator is saved in a memory store. Because the system is noisy (e.g., the speed of the pacemaker varies across trials), the number in the accumulator at the end of the same stimulus will vary across trials. Hence, the memory for the stimulus duration is represented not by a number but by a distribution of different numbers – typically a normal distribution. To make a temporal judgment, the subject compares the number currently in the accumulator (a measure of elapsed time) with

a number sampled from its memory store (a measure of the standard's duration). The judgment will depend on how close the two numbers are (see Gibbon, 1977, 1991; Grondin, 2010; Lejeune and Wearden, 2006; Wearden, 1991b).

Some results from timing tasks are easily accommodated within SET. We provide three examples. If a participant produces a 20-s interval when asked to produce a 15-s interval (the standard), one can conclude that the number of pulses the subject associates with 1 (subjective) second require more than 1 second to be generated, or that the subjective time unit is longer than the physical time unit. One could also say that the internal clock is slower than the external clock, or that the subject overestimates the label "15 seconds", but underestimates the physical interval of 20 s.

As a second example, consider a subject that sees an experimenter produce a 15-s standard and then, when reproducing it, generates a 20-s interval. In this case, we cannot conclude anything about the relative speeds of the internal and the external clocks or about the relative lengths of the psychological and the physical time units, for differences in speeds or units can still yield accurate reproductions of the standard. However, we can conclude that the speed of the internal clock decreased from the moment the standard was presented to the moment it was reproduced. To see this, suppose that initially the pacemaker emitted 1 pulse per second on the average. Then, at the end of the standard, the accumulator would register 15 pulses and this number would be saved in memory. If subsequently the speed of the pacemaker decreased to 0.75 pulses per second, the subject would need 20 s on the average to reproduce the 15 pulses associated with the standard.

Finally, in a discrimination task, suppose that the subject learns to classify a 0.5-s standard as "Short" and a 1.0-s standard as "Long" on the basis of the different number of pulses associated with each stimulus, say, 5 and 10 on the average. Subsequently, if the speed of the internal clock increases, the standard previously classified as "Short" may now be classified as "Long" because the number of pulses emitted in its presence may have increased from 5 to 10. We could say that the standards were now overestimated. SET then provides a clear conceptual framework to describe and analyze timing data.

In this article we use SET to understand how timing may be affected by motion. Moving stimuli tend to be perceived as longer than static stimuli (see, Kanai et al., 2006; Matthews, 2011) and similar effects occur when it is the participant, instead of the stimulus, that moves (Binetti et al., 2010; Capelli et al., 2007; Capelli and Israël, 2007; Israël et al., 2004; Vercruyssen et al., 1989). Participant whole-body motion can be further subdivided into active or passive according to whether the movements are or are not intentionally produced by the participant. Vercruyssen et al. (1989) studied the effect of active motion (whole-body motion without displacement in space) on time perception. Participants pressed a button to produce 10-s intervals while riding an ergometer cycle at a constant velocity. The intervals produced while riding the cycle were shorter than the intervals produced either before or after cycling, a result that suggests that the internal clock ran faster while riding the cycle.

Israël et al.'s (2004) study addressed the effects of passive motion. Participants were blindfolded and then either moved passively forward and backward (pushed by a machine) or did not move. In both conditions they were instructed to press a button once every second. Results showed that the production of 1-s intervals was more variable in the condition with motion than in the condition without motion. Furthermore, the frequency of button presses was correlated with acceleration. Positive acceleration reduced the inter response times (IRTs), negative acceleration increased the IRTs, and no acceleration (no motion or motion at a constant velocity) did not affect time production (see also, Capelli et al., 2007). Similar effects were found during rotational motion

(e.g., Binetti et al., 2010) and after rotational motion (Capelli and Israël, 2007).

Israël et al. (2004) suggested that time perception was disrupted because their procedure was effectively a dual-task procedure (Zakay, 1993), that is, a procedure in which two tasks were performed simultaneously, one task being the perception of physical displacement and the other task being the production of 1-s intervals. The effect of motion on time perception could be due to the interference of the non-temporal task on the concurrently performed temporal task (e.g., Binetti et al., 2010; Capelli et al., 2007; Capelli and Israël, 2007; Israël et al., 2004; Vercruyssen et al., 1989).

Other studies have shown that timing in dual-task conditions tends to be more inaccurate than in single-task conditions. Thus, produced or reproduced judgments differ more from the standard and vary more across trials in dual than single tasks and, similarly, the classification of standard durations is more error prone and varies more across trials in dual than single tasks (e.g., Brown, 1997, 2006; Wearden et al., 2010). To illustrate, Hwang et al. (2010) compared the performance of children and adolescents with attention-deficit/hyperactivity disorder (ADHD) to that of a control group without ADHD. The participants performed a reproduction task under a dual-task paradigm in which the non-temporal task involved counting visual stimuli presented on the computer screen. The results showed that the judgments of ADHD children and adolescents were less precise and accurate than those of the control group. Moreover, the simultaneous performance of a non-temporal task increased the number of time estimation errors in both groups, although the errors were more pronounced in the ADHD group.

Dual-task effects on timing occur also with animals. Lejeune et al. (1999) exposed pigeons to two tasks, a temporal task involving stimuli of different durations, and a non-temporal task involving a variable-ratio (VR) reinforcement schedule. In the single-task condition the pigeons performed only the temporal task and in the dual-task condition they performed both tasks concurrently. Specifically, in the temporal task the pigeons learned to choose one of two keys following a Short stimulus, and to choose the other key following a Long stimulus (bisection task). In the test phase, stimuli with intermediate durations were also presented and the pigeons' choices ('Short' or 'Long') were recorded. In the dual task condition, the pigeons needed to respond during the stimulus presentation. The percentage of 'Long' responses was lower when the pigeons performed the two tasks concurrently than when they performed only the temporal task.

To explain the results obtained with the dual-task paradigm, Zakay (1993) proposed the *Attentional Allocation Model*. This model states that attentional capacity is limited. Therefore, in a dual-task condition, the non-temporal and temporal tasks compete for these limited attentional resources such that, in the dual task, the participant may "miss" parts of the to-be-estimated duration (see Lejeune et al., 1999). That is, with the split of resources between the two tasks, attention to the standard may start only after its onset, be suspended during its occurrence, or stop before its offset. More generally, if accurate time judgments depend on directed attention, then any competing task that takes attention away from the temporal task will result in seemingly shorter standards (see also Zakay and Block, 1997). Phrased in terms of SET, the *Attentional Allocation Model* states that in the dual-task condition the pulses emitted during the standard may be lost and, consequently, the standard may seem shorter than in the single-task condition.

Casual observations suggest that humans may often engage in dual tasks one of which involves a temporal judgment and the other involves some form of motion. For example, a pedestrian may need to estimate the time to cross a busy street safely while walking or running. Given the high adaptive value of temporally regulated

behavior and given that humans are active agents often moving while executing many tasks, the question arises, how does active motion affect temporal discrimination? This then is the main question asked in the present study.

To answer the question, we exposed subjects to a temporal dual-task procedure (Israël et al., 2004). In the non-temporal task, participants ran on a treadmill, and in the temporal task, they performed either a temporal bisection task (Experiment 1), or a temporal generalization task (Experiment 2), two common tasks used to study timing in humans (e.g., Allan and Gibbon, 1991; Wearden, 1991a). We compared the performance in the temporal tasks when the participants were running on the treadmill (dual-task condition) with performance when they were standing still (single-task condition).

The literature on temporal dual-task procedures (e.g., Brown, 1997, 2008; Hwang et al., 2010; Zakay, 1993) indicates that the non-temporal task disrupts the performance on the temporal task and the *Attentional Allocation Model* states that this disruption may be due to a loss of pulses during the standard in the dual-task condition. Because a loss of pulses is equivalent to a decrease in pacemaker speed, one could say that in the dual-task condition the pacemaker was slower than in the single-task condition and for that reason the subject judged the same standard as shorter in the dual-task than in the single-task condition. However, the studies in which the non-temporal task involves active, whole-body motion show that produced intervals are generally shorter with motion than without motion, a result more consistent with an increase in pacemaker speed. For when the pacemaker emits pulses faster, any reference number of pulses will be reached earlier, and for that reason produced intervals will be shorter in the dual-task than in the single-task condition.

The present study extended the analysis of the effects of active motion to temporal discrimination tasks. If motion disrupts attention during the standard, with concomitant loss of pulses, then the subject will judge the standard shorter in the dual-task than in the single-task condition. In contrast, if motion increases the speed of the pacemaker, the subject will judge the standard longer in the dual-task than in the single-task condition.

## 2. Experiment 1

Experiment 1 compared time perception under the two conditions of a dual-task procedure. In the single-task condition the participants performed only a temporal bisection task, and in the dual-task condition they performed the temporal bisection task while running on a treadmill.

Walking or running on a treadmill removes the translational component of motion, but preserves all the rotational-pendular components. In particular, it preserves the fundamental biomechanical, perceptual and egomotion properties of regular motion. In terms of biomechanical properties, free walking and walking on a treadmill are similar. In terms of perception, almost all experiments on biological motion perception performed since the seminal studies of Gunnar Johansson in the 1970s have removed the translational component; nevertheless, recognition of motion patterns and even complex actions remains straightforward for both humans and animals. And in terms of egomotion perception, the vection experience (visual expansion) and the feeling of acceleration may be reduced while walking on a treadmill, but all the other multisensory motion cues including visual and vestibular inputs coupled with rhythmic postural changes, auditory (step sounds) and somatosensory (motion of the limbs) cues remain intact (see Johansson, 1973, 1976). Hence, walking and running on a treadmill should still be regarded as a locomotion pattern.

**Table 1**
Order of each condition in each session for the two groups of participants. S = single and D = dual task.

| | Order of conditions presentation | | | |
|---|---|---|---|---|
| | Session 1 | | Session 2 | |
| Group | Condition 1 | Condition 2 | Condition 1 | Condition 2 |
| S-D:D-S | Single-task | Dual-task | Dual-task | Single-task |
| D-S:S-D | Dual-task | Single-task | Single-task | Dual-task |

### 2.1. Method

#### 2.1.1. Participants
Ten undergraduate students (5 females, mean age = 25.3, SD = 2.0) from the University of Minho voluntarily participated in the experiment. The participants had no previous experience with the procedure and were blind to the hypothesis of the study.

#### 2.1.2. Setting, apparatus, and stimuli
The experimental sessions were conducted in a 10 m × 7 m room at the University of Minho (http://webs.psi.uminho.pt/lvp). The room was equipped with a treadmill (Valiant 932900SE) and a safety harness attached to the ceiling and used to prevent injuries in case the participant fell off the treadmill (which never occurred in the present studies). Approximately 20 cm in front of the treadmill was a table with a laptop computer, a pair of headphones, and a wireless mouse. The computer presented the instructions, controlled the stimulus presentations, and registered the mouse responses.

#### 2.1.3. Procedure
Before each session, the participants were asked to put on the safety harness and the headphones, hold the wireless mouse in their preferred hand, and stand up on the treadmill.

As Table 1 shows, each experiment comprised two sessions, each approximately 25-min long, with a 2-h break between sessions. During each session, there were two conditions, single-task (S) and dual-task (D), each lasting approximately 10 min, with a 2-min break between them. In the single-task condition, the participants performed only the temporal task. In the dual-task condition the participants performed the temporal task simultaneously with the non-temporal task. The difference between the two sessions was the order of the conditions. The participants were divided into two groups according to the order of the conditions: Group S-D:D-S started with the single-task condition, and Group D-S:S-D started with the dual-task condition.

At the beginning of the first session, the following instructions were presented on the computer screen:

> "Thank you for participating in our study. We are interested in some features of behavior that are common to all people. More specifically, we are interested in the sense of time that each person has. I will present to you two tones, one short and one long. Pay attention to both and tell me if you can hear them clearly. When ready to begin, please say so."

Next, the two anchor stimuli, a 300-ms (Short) and a 700-ms (Long) tone, both 500-Hz in frequency, were presented in alternation, three times each, always starting with the short stimulus. After the presentation of the anchor stimuli, the following instructions were provided at the beginning of each condition:

> "You will see a black square on the computer screen. Then you will hear a tone. When the tone ends, the square will turn yellow. At this moment, you will have to click one of the two mouse buttons. If the tone seems LONG, click the RIGHT button of the

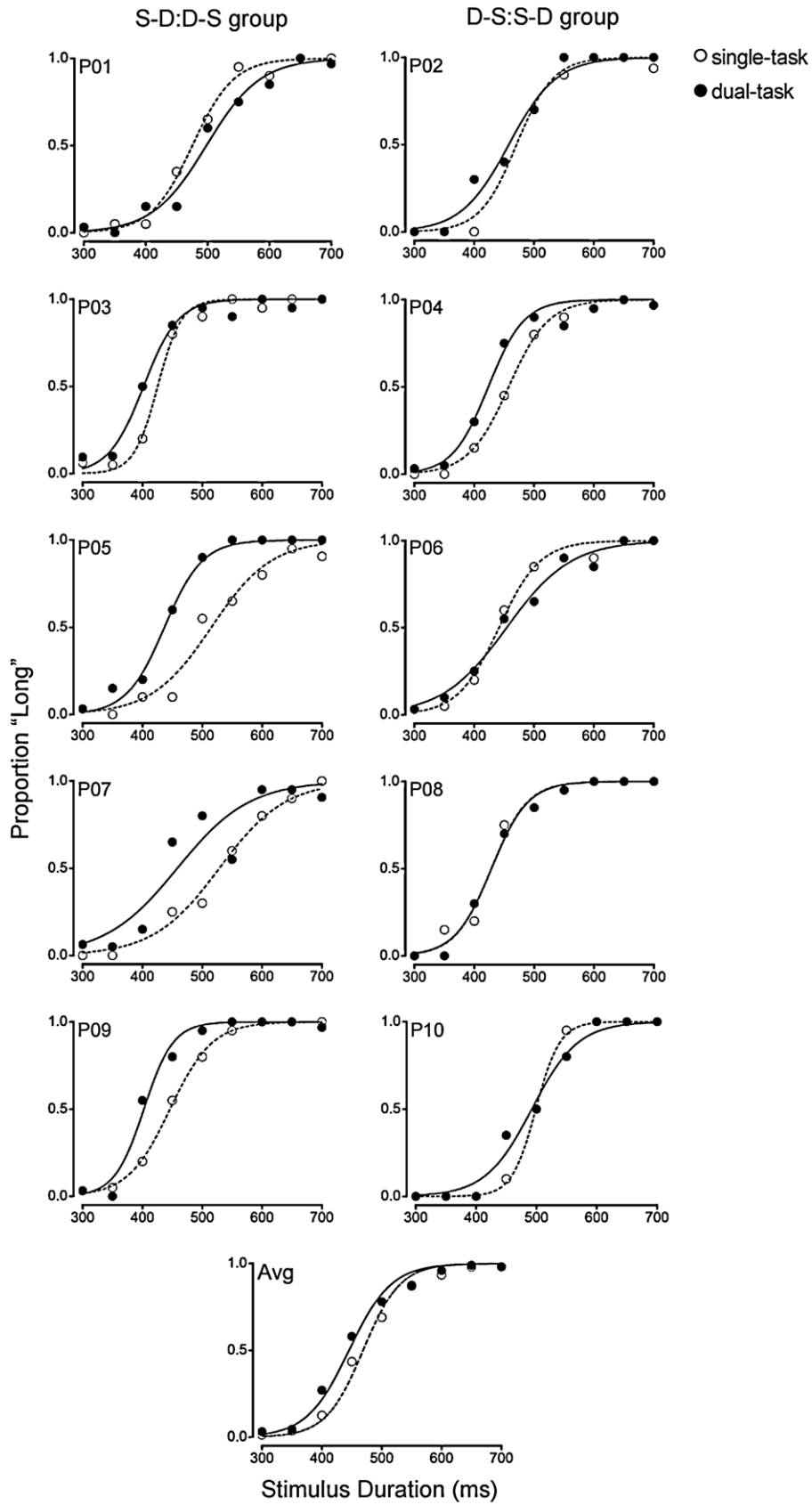**Fig. 1.** Individual and average proportion of "Long" responses plotted as a function of stimulus duration. The left and right panels show the data from groups S-D:D-S and D-S:SD, respectively. The last row shows the average data. Open and close circles show the data from the single- and dual-task conditions, respectively. The lines are the best-fit cumulative Gaussian (parameters in Table 2).

mouse. If the tone seems SHORT, click the LEFT button of the mouse.

Click any mouse button to start."

Regardless of condition, single- or dual-task, these instructions and the presentation of the anchor stimuli occurred with the treadmill off. The aim of these instructions was to ensure the learning of the correct responses to the anchor stimuli. The mapping between the left and right responses and the short and long stimuli was reversed for half of the participants. Henceforth, the correct responses following the Long and Short stimuli will be designated "Long" and "Short", respectively.

After reading the instructions and hearing the anchor stimuli, the participants in the dual-task condition were asked to run on a treadmill at a speed of 2 meters per second (m/s). This velocity was achieved by increasing the speed of the treadmill gradually for about one minute. After the participants were running at the target speed of 2 m/s for one additional minute, the temporal task began. In the single-task condition, after reading the instructions and hearing the anchor stimuli, the participants waited two minutes before the temporal task began. Once the temporal task began the only difference between the two conditions was that the participants were running in one case, and standing still in the other case.

In the temporal task, the two anchor stimuli and seven new stimuli (intermediate stimuli) were presented across trials in random order. The intermediate stimuli, also 500-Hz tones, had the following durations: 350, 400, 450, 500, 550, 600, and 650 ms. After the presentation of each stimulus, the participants had to click one of the mouse buttons. Thus, one trial comprised the stimulus presentation and the participant's response. None feedback was provided. The inter-trial interval (ITI) could be 1-s or 3-s long, randomly determined.

Each condition ended after 16 presentations of each anchor stimulus and 10 presentations of each intermediate stimulus, for a total of 102 trials.

### 2.1.4. Data analysis

For each stimulus duration, $t$, we computed the corresponding proportion of "Long" responses, $P(\text{"Long"}|t)$. These proportions define the psychometric function, which typically follows a sigmoid curve, starting close to 0 at the shortest duration and ending close to 1 at the longest duration. The curve is generally well fit by a cumulative Gaussian function with two parameters, the mean, $\mu$, and the standard deviation, $\sigma$. The mean corresponds to the Point of Subjective Equality (PSE), that is, the duration that yields indifference between the "Long" and "Short" responses; hence, $P(\text{"Long"}|t=\mu)=.5$. The standard deviation is inversely related to the participants' sensitivity to stimulus duration (smaller values of $\sigma$ correspond to steeper curves and higher temporal sensitivity).

We used ANOVAs to compare the obtained psychometric functions and their estimated parameters across conditions and sessions. Because a preliminary analysis showed no systematic differences between the two psychometric functions from the single-task conditions and between the two psychometric functions from the dual-task conditions (see order in Table 1), we averaged them. Thus, each participant contributed two psychometric functions, one from condition Single and one from condition Dual. Significance level was set at $p < .05$.

### 2.2. Results and discussion

Fig. 1 shows the obtained psychometric functions. The left and right panels show the data for the S-D:D-S and D-S:S-D groups, respectively. The bottom graph shows the data averaged across groups. The open and closed circles are the data from the

**Table 2**
Best-fitting parameters from cumulative Gaussian curve ($\mu$ = mean, $\sigma$ = standard deviation) and variance accounted for ($\omega^2$) in Experiment 1. Ptc = participant.

| Group | Ptc | $\sigma$ | | $\mu$ | | $\omega^2$ | |
|---|---|---|---|---|---|---|---|
| | | Single | Dual | Single | Dual | Single | Dual |
| S-D:D-S | 01 | 55.55 | 74.89 | 475.28 | 498.59 | 0.99 | 0.98 |
| | 03 | 31.99 | 47.78 | 425.23 | 401.75 | 1.00 | 0.98 |
| | 05 | 84.28 | 54.43 | 515.71 | 436.37 | 0.97 | 0.99 |
| | 07 | 94.54 | 102.98 | 527.81 | 460.46 | 0.99 | 0.86 |
| | 09 | 59.91 | 41.71 | 446.37 | 403.40 | 1.00 | 0.98 |
| D-S:S-D | 02 | 51.42 | 67.20 | 471.14 | 457.10 | 0.99 | 0.98 |
| | 04 | 56.44 | 48.83 | 457.48 | 423.31 | 1.00 | 0.99 |
| | 06 | 57.54 | 90.89 | 441.37 | 454.61 | 0.99 | 0.98 |
| | 08 | 52.93 | 51.72 | 428.38 | 428.88 | 0.98 | 0.99 |
| | 10 | 34.85 | 64.68 | 498.76 | 492.12 | 1.00 | 0.99 |
| Average | | 57.95 | 64.51 | 468.75 | 445.66 | 0.99 | 0.97 |

single-task and dual-task conditions, respectively. The lines are the best-fit cumulative Gaussian curves. In the bottom panel, the lines show the curves obtained from averaging the individual best-fit Gaussian curves. Table 2 shows the estimated parameters and the variance accounted for ($\omega^2$).

For both groups and conditions, the proportion of "Long" responses tended to increase monotonically with stimulus durations from about 0 to about 1, which reveals good temporal discrimination between the anchor stimuli. A mixed $9 \times 2 \times 2$ ANOVA, with groups (2 levels) as between-subjects factor, and stimulus duration (9 levels) and experimental condition (2 levels) as within-subjects factors, showed a significant effect of duration, $F(8, 64) = 218.93$, $p < .001$, $\eta_p^2 = .96$, and a significant interaction between stimulus duration and condition, $F(8, 64) = 2.98$, $p = .007$, $\eta_p^2 = .27$. All other effects were not significant. These results revealed that the participants' responses varied with stimulus duration and that the variation differed between experimental conditions.

To further examine how time perception varied with experimental condition, we compared the estimated parameters of the psychometric functions from the single-task and dual-task conditions. The standard deviations ranged from 31.99 to 94.54 ($M = 57.95$, SD = 19.20) in the single-task condition and from 41.71 to 102.98 ($M = 64.51$, SD = 20.00) in the dual-task condition (see Table 2). A mixed $2 \times 2$ ANOVA comparing the standard deviations ($\sigma$ values) of the two groups as between-subjects factor and the two conditions as within-subjects factor, revealed no significant effect of either factor or of their interaction (all $F$s < 1.4, $p$ > .27). Thus we can reject the hypothesis that sensitivity to time was affected differentially by the experimental condition (single- or dual-task) or by the order in which the conditions were presented. Any interference effects of running were not large enough to disrupt temporal discrimination.

However, visual inspection of the average data suggests that the curves of the two conditions had different PSEs. Individual PSEs ($\mu$ values) ranged from 425.23 to 527.81 ms ($M = 468.75$; SD = 35.81) in the single-task condition and from 401.75 to 498.59 ms ($M = 445.66$, SD = 33.29) in the dual-task condition (see Table 2). A mixed $2 \times 2$ ANOVA comparing the PSEs of the two groups (between factor) and two conditions (within factor) revealed that the mean PSE in the single-task condition were significantly different from the mean PSE in the dual-task condition, $F(1, 8) = 5.46$, $p = .048$, $\eta_p^2 = .41$, but there was no effect of group or interaction between the two factors (all $F$s < 2.3, $p$ > .17). This result indicates that, in general, under the dual-task condition the participants had more "Long" responses then in the single-task condition.

In sum, the results revealed that the participants' responses were not differentially sensitive to the stimulus durations in the

single- and dual-task conditions, so concurrent execution of a non-temporal task did not alter temporal sensitivity. However, as the difference in the PSE between conditions and the significant inter-action between stimulus durations and conditions revealed, the participants perceived stimulus durations, particularly the inter-mediate durations, as longer when they were running.

This result is consistent with Capelli et al. (2007), Israël et al. (2004), and Vercruyssen et al. (1989) studies which found that, when producing 1-s or 10-s intervals by pushing a button, passive and active motion shortened the IRTs. Participants seem to perceive the same standard as longer when moving than when remaining stationary. However, there seems to be a difference between pas-sive and active motion. With passive motion the effect did not occur when there was no acceleration (i.e., no motion or motion at con-stant velocity; e.g., Capelli et al., 2007; Israël et al., 2004), but with active motion the effect was found under constant velocity (present Experiment 1; Vercruyssen et al., 1989).

The magnitude of the shift in the psychometric function obtained in the present study is within the range of the shifts obtained with human participants when other variables are manip-ulated in the temporal bisection task. One way to quantify the magnitude of the shift is to divide the absolute difference between the PSEs obtained in each condition by the average PSE,

$$\frac{\left|\text{PSE single} - \text{PSE dual}\right|}{(\text{PSE single} + \text{PSE dual})/2} \times 100.$$

In the present study, the magnitude of the shift was 5.05%. Gil and Droit-Volet (2011) obtained a shift of 6.8% when investigat-ing the effect of angry faces on time perception. Droit-Volet and Wearden (2002) obtained a shift of 8.7% with 8-year olds when investigating the effects of a flicker training on time perception. And McCormack et al. (1999) obtained a shift of 6.9% when compar-ing time perception in 5-year olds and undergraduate students. We conclude that the effect obtained in the present study is consistent with the effects obtained in other studies.

The present study cannot rule out an alternative account of the overestimation effect. Instead of an increase in pacemaker speed, the overestimation effect could be due simply to a shift of context, form standing still while hearing the standard tones, to running in the treadmill while hearing the test tones. To test this account, the experimenter could present the standard tones while the partici-pants were running and then present the test tones while they were standing still. Effects in the opposite direction to that reported in the present paper would be strong evidence for the pacemaker-based account advanced above.

## 3. Experiment 2

The aim of Experiment 2 was to investigate the effect of motion on temporal generalization. Participants were asked to evaluate if a set of comparison tones varying in duration were equal to, or different from, a standard tone. As in Experiment 1, we compared performance on the generalization task under two conditions, a dual-task condition in which the participants ran on a treadmill while hearing and classifying the stimuli, and a single-task con-dition in which the participants stood still on the treadmill while hearing and classifying the stimuli.

For the single-task condition we expected a roughly bell-shaped generalization gradient centered on the standard duration (Wearden, 1991b). In the dual-task condition, if motion increases subjective duration, as Experiment 1 suggested, then we expected a gradient shifted to the left. For if active motion speeds the pace-maker and thereby inflates durations, as it were, then durations somewhat shorter than the standard should be perceived as equal

to the standard, but durations somewhat longer than the standard should be perceived as even longer and therefore more unequal to the standard than before; the net effect should be a leftward shift in the generalization gradient.

### 3.1. Method

#### 3.1.1. Participants

Ten volunteer undergraduate students from the University of Minho participated in the experiment (six females and four males, mean age = 25.2, SD = 1.54). The participants had no previous expe-rience with the experimental procedure and were blind to the hypothesis of the study.

#### 3.1.2. Procedure

Similar to Experiment 1 (see Table 1) the participants were ran-domly divided into two groups, one exposed to the single- and dual-task conditions in the order S-D:D-S, and one exposed to the two conditions in the order D-S:S-D. The two conditions, about 10 min each, were separated by a 2-min break. The two sessions, each approximately 25-min long, were separated by a 2-h break.

At the beginning of the first session, the following instructions were presented on the computer screen:

"Thank you for participating in our study. We are interested in some features of behavior that are common to all people. More specifically, we are interested in the sense of time that each person has. I will present to you a CORRECT tone. Pay attention to its duration and tell me if you can hear it clearly. When ready to begin, please say so."

After the instructions, the standard stimulus, a 500-Hz tone lasting 500 ms, was presented five times. Next, a second set of instructions was provided:

"You will see a black square on the computer screen. You will hear a tone. When the tone ends, the square will turn yellow. At this moment, you will have to click one of the two mouse buttons. If the tone seems EQUAL to the CORRECT tone, click the RIGHT mouse button. If the tone seems DIFFERENT, click the LEFT button. Click any mouse button to start."

The mapping between the right/left buttons and the equal/different judgments was counterbalanced across partic-ipants. Hence, instead of "Left" and "Right", we refer to the two responses as "Equal" and "Different".

The instructions and the five presentations of the standard tone were repeated at the beginning of each condition with the par-ticipants standing still on the treadmill. Then, in the dual-task conditions the treadmill was turned on in the manner described in Experiment 1. In both conditions, the temporal generalization task began 2 min later.

There were nine 500-Hz comparison stimuli varying in duration, four shorter, one equal, and four longer than the 500-ms standard: 300, 350, 400, 450, 500, 550, 600, 650, and 700 ms. Henceforth, the comparison stimulus with the same duration as the standard will be named "equal-comparison". After the presentation of each stimulus, the participant had to press one of the mouse buttons. No feedback was provided. As in Experiment 1, the stimulus presen-tation and the response constituted a trial and the ITI equaled 1 or 3 s, randomly determined.

Each session ended after 128 trials, 64 in which the 500-ms, equal-comparison duration was presented, and 64 in which the 8 different-comparison durations were presented (for 8 trials each). The order of stimulus presentations was randomized across trials.

**Table 3**
Best-fitting parameters from cumulative Gaussian curve ($\mu$ = mean, $\sigma$ = standard deviation) and variance accounted for ($\omega^2$) in Experiment 2. Ptc = participant.

| Group | Ptc | $\sigma$ value | | $\mu$ value | | $A$ value | | $\omega^2$ | |
|---|---|---|---|---|---|---|---|---|---|
| | | Single | Dual | Single | Dual | Single | Dual | Single | Dual |
| S-D:D-S | 01 | 138.13 | 153.19 | 575.88 | 595.01 | 307.85 | 258.75 | 0.85 | 0.75 |
| | 03 | 119.25 | 143.25 | 557.31 | 579.79 | 281.97 | 354.96 | 0.97 | 0.94 |
| | 05 | 60.17 | 80.95 | 506.77 | 490.15 | 133.79 | 178.16 | 0.94 | 0.94 |
| | 07 | 103.82 | 123.19 | 496.18 | 554.35 | 273.79 | 313.87 | 0.97 | 0.86 |
| | 09 | 147.86 | 191.60 | 564.08 | 522.77 | 287.02 | 349.61 | 0.95 | 0.82 |
| D-S:S-D | 02 | 91.02 | 123.39 | 551.78 | 567.18 | 247.37 | 301.70 | 0.93 | 0.95 |
| | 04 | 81.00 | 121.96 | 512.23 | 511.61 | 182.44 | 211.94 | 0.94 | 0.76 |
| | 06 | 89.99 | 182.00 | 429.20 | 549.91 | 178.62 | 346.62 | 0.89 | 0.76 |
| | 08 | 149.27 | 202.22 | 527.64 | 433.23 | 397.51 | 334.04 | 0.83 | 0.82 |
| | 10 | 130.25 | 180.39 | 534.91 | 605.14 | 267.18 | 263.98 | 0.82 | 0.81 |
| Average | | 111.08 | 150.21 | 525.60 | 540.91 | 255.75 | 291.36 | 0.91 | 0.84 |

### 3.1.3. Data analysis

The generalization gradients relating the proportion of "Equal" responses to the stimulus duration were fitted by a Gaussian density function with equation

$$P(\text{"Equal"}|t) = A \frac{e^{-(1/2)((t-\mu)/\sigma)^2}}{\sqrt{2\pi}\sigma}$$

where $P(\text{"Equal"}|t)$ is the proportion of "Equal" responses given a $t$-s stimulus, $\mu$ and $\sigma$ are the mean and standard deviation of the Gaussian function, respectively, and $A$ is a (vertically) scaling parameter that, combined with $\sigma$, determines the overall probability of reporting "Equal". As in Experiment 1, a preliminary analysis showed no significant differences between the two gradients from the single-task conditions and between the two gradients from the dual-task conditions (see order in Table 1), hence we averaged them. Thus, each participant contributed two psychometric functions, one from condition single and one from condition dual.

### 3.2. Results and discussion

Fig. 2 shows the individual and average proportion of "Equal" responses plotted as a function of stimulus duration. The left panel shows the data from the S-D:D-S group, and the right panel presents the data from the D-S:S-D group. The open and closed circles show the average data from the single- and dual-task conditions, respectively. The lines show the best-fitting curves. In the bottom panel, the lines show the averages of the individual curves. Table 3 shows the corresponding parameters as well as the variance accounted for.

To compare the generalization gradients we ran a mixed $9 \times 2 \times 2$ ANOVA having the nine comparison durations and the two conditions as within-subjects factors and the two groups as between-subjects factor. The analysis revealed significant effects of duration, $F(8, 64) = 29.50$, $p < .001$, $\eta_p^2 = .79$, and interaction between duration and condition, $F(8, 64) = 2.58$, $p = .017$, $\eta_p^2 = .24$; no other effects were significant (all $F$s < 1, $p > .5$).

The proportion of "Equal" responses yielded generalization gradients that were reasonably well fit by the Gaussian functions, with $\omega^2$ values ranging from .75 to .97 ($M = .87$, SD = .08; see Table 3). The $\mu$ parameters ranged from 429.20 to 575.88 ms ($M = 525.6$, SD = 42.79) in the single-task condition and from 433.23 to 605.14 ms ($M = 540.91$, SD = 52.57) in the dual-task condition. A mixed $2 \times 2$ ANOVA comparing the individual $\mu$ values of the two groups (between factor) and the two conditions (within factor) revealed no significant effect of condition, group or their interaction (all $F$s < .9, $p > .3$). Thus, contrary to the hypothesis, there were no systematic differences in the mean of the gradients between the single and dual-task conditions.

Concerning the width of the generalization gradients, the average data suggests that the curves from the dual-task condition were flatter than the curves from the single-task condition. The $\sigma$ parameters ranged from 60.17 to 149.27 ($M = 111.08$, SD = 30.5) in the single-task condition and from 80.95 to 202.22 ($M = 150.21$, SD = 38.65) in the dual-task condition. A mixed 2x2 ANOVA with group (between) and condition (within) factors revealed a significant effect of condition, $F(1, 8) = 47.16$, $p < .001$, $\eta_p^2 = .85$, because the $\sigma$ values were smaller in the single-task condition ($M = 111.08$) than the dual-task condition ($M = 150.21$), and a significant effect of the interaction between group and condition, $F(1, 1) = 6.51$, $p = .034$, $\eta_p^2 = .45$, because the difference mentioned above was bigger for group D-S:S-D than group S-D:D-S; there was no effect of group ($F < .2$, $p > .6$). These results suggest better temporal control under the single-task condition. That is to say, running affected the precision with which participants identify the duration of intervals.

The individual $A$ values ranged from 133.79 to 397.51 ($M = 255.75$, SD = 75.42) in the single-task condition and from 178.16 to 354.96 ($M = 291.36$, SD = 61.34) in the dual-task condition (see Table 3). A mixed $2 \times 2$ ANOVA yielded no effect of condition, group or interaction between these factors (all $F$s < 2.7, $p > .09$).

We also fit the generalization gradients with a more specific instantiation of SET (Church and Gibbon, 1982). Assume that the subject's representation of the standard is a Gaussian random variable $X_S$ with mean $\mu$ and standard deviation proportional to the mean, $\gamma \times \mu$. Moreover, when presented with a stimulus of duration $t$, the participant responds "Equal" provided the relative difference $|(X_S - t)/X_S|$ is less than a threshold, $b$. Church and Gibbon (1982) assumed a variable threshold, but here we explore the simpler case of a constant threshold. From the previous assumptions, it follows that the probability of an "Equal" response after a $t$-s stimulus is

$$P(\text{"Equal"}|t) = \Phi(z_2) - \Phi(z_1)$$

where $\Phi(z)$ is the standard cumulative normal distribution, and $z_1$ and $z_2$ are defined as follows

$$z_1 = \frac{1}{\gamma}\left(1 - \frac{1}{1-b}\frac{t}{\mu}\right), \qquad z_2 = \frac{1}{\gamma}\left(1 - \frac{1}{1+b}\frac{t}{\mu}\right)$$

This specific model has three parameters ($\mu$, $\gamma$, and $b$), the same number as the Gaussian density model with a scale factor ($\mu$, $\sigma$, and $A$). In fact, the first two parameters of each model are equivalent, for in both cases they characterize the mean and variability of the representation of the standard. The third parameter, the threshold, is similar to the scaling factor A, for increasing b or A increases $P(\text{"Equal"}|t)$. Given these similarities we expect the new model to fit the data equally well, and to yield parameter values that do not alter significantly the interpretations based on the Gaussian density model. However, because the new model assumes a ratio decision rule it can generate gradients that are not Gaussian
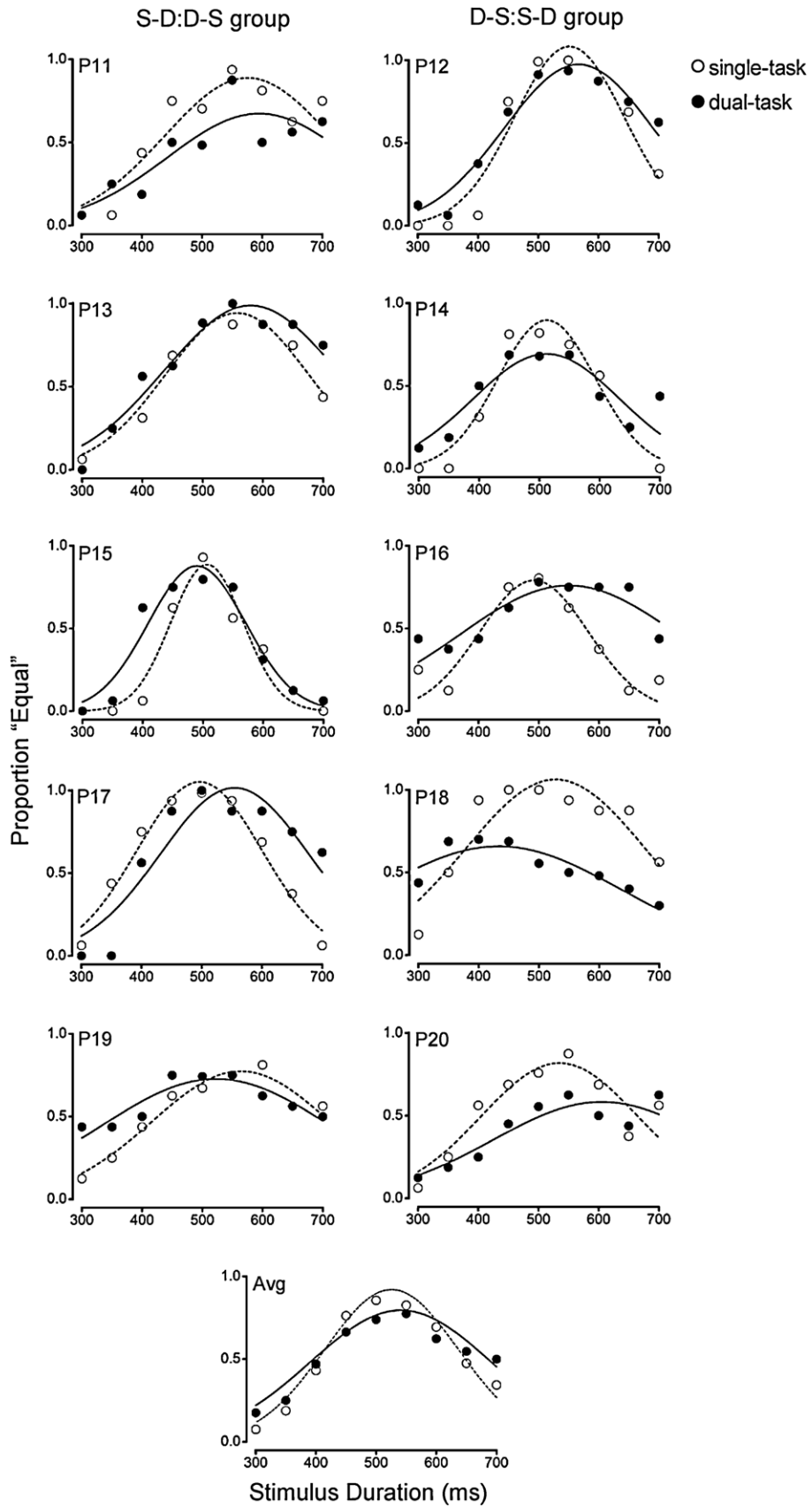
**Fig. 2.** Individual and average proportion of "Equal" responses plotted as a function of stimulus duration. The left and right panels show the data from groups S-D:D-S and D-S:SD, respectively. The last row shows the average data. Open and close circles show the data from the single- and dual-task conditions, respectively. The lines are the best-fit Gaussian curves (parameters in Table 3).

and, in particular, gradients that are asymmetric (notice that the difference between the two cumulative Gaussians, $\Phi(z_2) - \Phi(z_1)$, is not itself a Gaussian density).

The new model fit the data slightly better than the previous model: $\omega^2$ values averaged $M = .90$ (against $M = .87$). However, statistical analyses (mixed ANOVAs) comparing the $\mu$, $\gamma$, and $b$ parameters as a function of group (S-D:D-S vs. D-S:S-D) and condition (single task vs. dual task) yielded the exact same results as before: neither the mean ($\mu$) nor the threshold ($b$) varied with group or condition, but variability ($\gamma$) increased in the dual task condition, particularly for group D-S:S-D. In fact, the parameter values of the two models were significantly correlated (range of correlation coefficients, .68–.99). These results corroborate the idea that running affected mainly the precision with which the participants identified the duration of the intervals.

In sum, the generalization gradient from the dual-task condition was significantly wider than the gradient from the single-task condition, which means that temporal control was reduced, particularly when the participants started the experiment by running on the treadmill.

## 4. General discussion

The experiments reported above evaluated the effect of active motion on time perception. In Experiment 1, participants performed a temporal bisection task while running (dual-task condition) or standing still (single-task condition). Results showed that under the dual-task condition durations were perceived as longer than under the single-task condition. In Experiment 2, participants performed a temporal generalization task also while running or standing still. Results showed that motion weakened temporal control. Taken together, these results indicate that the way motion affects time perception depends on the temporal task.

In what follows, we compare our findings with the predictions of the *Attentional Allocation Model* (e.g., Zakay, 1993; Zakay and Block, 1997). Then, we describe, in more detailed, the comparison/decision component of SET and consider ways in which this model may account for the effects of running. Finally we compare the suggested account with the results from the temporal bisection and generalization tasks.

### 4.1. Attentional Allocation Model

As mentioned before, according to Zakay (1993), in a dual-task paradigm the non-temporal and temporal tasks compete for limited attentional resources. The resulting split in the allocation of attention reduces the storage of time clues, which in turn yields a poorer representation of a temporal interval. Because temporal judgments rely on the internal representations, it follows that, with a reduced number of stored time cues, a shortening in the time estimate occurs, and this in turn yields the perception of shorter intervals in temporal discrimination tasks (Brown, 1997, 2008; Zakay and Block, 1997). The model is consistent with the well-documented effect that participants underestimate physical time when performing a non-temporal task concurrently (e.g., Brown, 1997; Hemmes et al., 2004; Kladopoulos et al., 2004).

However, the results found in studies that used a whole-body motion as the non-temporal task (Binetti et al., 2010; Capelli et al., 2007; Capelli and Israël, 2007; Israël et al., 2004; Vercruyssen et al., 1989), as well as the results obtained in the present study, are the opposite of the results predicted by the *Attentional Allocation Model*. Under a concurrent non-temporal task that involved whole-body motion (passive or active), the participants perceived time as longer rather than shorter, that is, they overestimated physical time.

Our results agree with Molet et al. (2011) finding that the effect of the non-temporal task varies with the nature of the task. Their findings show that when the non-temporal task required counting backwards by threes, physical time was underestimated. However, when the non-temporal task involved exerting continuous force on a transducer, the opposite effect was obtained, physical time was overestimated.

### 4.2. Scalar Expectancy Theory (SET)

The effects found under active motion may be interpreted in the light of Scalar Expectancy Theory (SET). In the temporal bisection task, the pulses accumulated during the short and long samples are stored in separate memories. In the temporal generalization task, the pulses accumulated during the standard stimulus are stored in the same memory. To decide whether a test stimulus is closer to the short or to the long samples (temporal bisection), or equal to or different from the standard sample (temporal generalization), the participant compares the pulses accumulated during the test stimulus with samples extracted from memory. The decision rule is slightly different in the two tasks. Thus, in the bisection task, SET assumes that the participant forms two ratios $X_t/X_S$ and $X_L/X_t$, where $X_t$ is the number of pulses in the accumulator at the end of the test stimulus, $X_S$ is a sample extracted from the memory associated with the short sample, and $X_L$ is a sample extracted from the memory associated with the long sample. If $(X_t/X_S) < \beta(X_L/X_t)$, where $\beta$ is a bias parameter, the participant responds "Short"; otherwise it responds "Long". In the temporal generalization task, the participant forms the ratio $X_t/X_S$, where $X_t$ is the number of pulses in the accumulator at the end of the test stimulus and $X_S$ is a sample extracted from the memory associated with the standard duration. It responds "Equal" provided the ratio $|X_S - X_t|/X_S < \beta$, and "Different" otherwise (e.g., Bangert et al., 2011; Gibbon, 1977, 1991; Grondin, 2010; Lejeune and Wearden, 2006; Wearden, 1991b).

If we assume that, in a temporal dual-task paradigm (when cognitive tasks of the type adding or counting numbers are implemented as the non-temporal task), divided attention causes loss of pulses in the accumulator, then the result is a shortening of perceived stimulus durations. But if we assume that non-temporal task such as running accelerate the pacemaker, then more pulses will be accumulated and the result will be a lengthening of perceived duration. Perhaps, then, the nature of the concurrent task will determine which effect will prevail. Tasks with or without motion may have different effects on the pacemaker–accumulator unit (loss of pulses or increase in rate of pulse generation).

We consider now how the foregoing ideas might account for the empirical findings. In Experiment 1 the participants perceived stimulus durations as longer when they performed the two tasks concurrently (temporal discrimination + running) compared to when they performed only the temporal task. This result can be explained by assuming an increase in the speed of the pacemaker – the same physical duration will yield a higher value of $X_t$ and therefore a higher probability of classifying the stimulus as "Long".

However, in a temporal generalization task, an increase in pacemaker speed will shift the baseline generalization gradient to the left. This prediction was not observed in Experiment 2, which showed a flattening rather than a shift of the generalization gradient during running. Before advancing an explanation for the flattening of the generalization gradient, consider what SET predicts if the pacemaker speed increases but the participant updates its memory for the standard duration with the new pacemaker speed. That is, suppose that the memory for the standard duration continues to be updated while the participant is running. In this case, the participant in the running condition is similar to the participant in the standing still condition in all respects except one, its pacemaker is faster. But in this case SET predicts no effect of running on the generalization gradient. In fact, it can be shown (Gibbon and Church, 1984) that according to SET, the temporal generalization

gradient does not depend on the absolute value of the pacemaker speed.

There are at least two ways to predict a flattening of the gradient with running. The most straightforward is to assume that the variability of the internal clock, represented in SET by the coefficient of variation of the pacemaker speed, increases with running. The problem with this hypothesis, however, is that it predicts a decrease in the slope of the psychometric function in the bisection task when the participant is running, a decrease that was not observed.

Another way to predict a flattening of the gradient is to assume that, during testing, the participant's memory for the standard duration is contaminated by other test samples, both shorter and longer than the standard. In this case, the denominator of the decision ratio would be equal to $X_S$ on some trials, greater than $X_S$ on other trials (the effect of test samples longer than the standard), and smaller than $X_S$ on still other trials (the effect of test samples shorter than the standard). The combined effect of the memory contamination will be a decrease in the proportion of "Equal" responses in the region of the standard duration and an increase in the proportion of "Equal" responses in the regions of the durations shorter and longer than the standard. In a word, the gradient will flatten by decreasing in the middle region and increasing in the tails, the observed effect.

The foregoing hypothesis suggests that running may have task specific effects or, more precisely, that it may have multiple effects but not all of them would be expressed in a specific task. On the one hand, speeding the pacemaker would be expressed in the bisection task by the increase in the proportion of "Long" responses, but it would not be expressed in the temporal generalization task because the memory for the standard would also change when the speed of the pacemaker increases. On the other hand, memory contamination would be expressed in the temporal generalization task by the flattening of the gradient, but it would not be expressed in the bisection task because its effect is canceled when two memory stores are involved. The foregoing hypothesis opens new avenues for research on the effects of running on time perception.

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