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Original Citation:

The role of physical and cognitive effort on time perception / Bartolini T., Petrizzo I., Arrighi R., Anobile G.. - In: SCIENTIFIC REPORTS. - ISSN 2045-2322. - ELETTRONICO. - 15:(2025), pp. 25595.0-25595.0. [10.1038/s41598-025-07814-9]

Availability:

The webpage <https://hdl.handle.net/2158/1451394> of the repository was last updated on 2026-02-07T06:30:00Z

Published version:

DOI: 10.1038/s41598-025-07814-9

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OPEN The role of physical and cognitive effort on time perception

Tommaso Bartolini^{1,2}, Irene Petrizzo^{3✉}, Roberto Arrighi⁴ & Giovanni Anobile⁴

Action and perception are intertwined, and time perception is not an exception to this general principle. In line with that, we have recently reported that the perceived duration of visual stimuli is extended while running. Here we tested the nature of this phenomenon by contrasting two possibilities: one related to physiological changes induced by physical effort (e.g. heart rate, temperature, arousal), and one related to cognitive alterations linked to motor control. To this aim we compared the direction and magnitude of the temporal bias induced by running to that prompted by other two conditions requiring much lower physical effort but both depleting cognitive resources. In these two conditions, participants either performed the timing task while walking backwards (an attentional motor task) or standing still with cognitive resources divided in a concurrent visual-working memory task. Both conditions yielded temporal overestimations virtually identical to that found while running, suggesting that physical activity could modulate temporal processing through the cognitive effort required to perform/control that specific motor routine. The results are informative for the scientific community investigating time perception in ecological sensorimotor contexts, suggesting the importance of considering the potential confounding role of cognitive factors related to motor execution.

Despite having an accurate perception of the passage of time is essential for many everyday activities, the subjective feeling of events' duration often does not match their physical (chronological) duration. Within the many factors shaping subjective duration, motor activity is one of the most investigated. It is now well established that time perception is intimately linked to the motor system. A variety of voluntary movements — including those of the fingers¹, hands^{2–4}, eyes^{5,6} and others — can strongly modulate the perceived duration of sensory inputs, often leading to underestimation or overestimation errors. Together with these specific actions, often performed by a single motor effector (e.g. eyes, hands, fingers), we also frequently perform movements involving the whole-body, such as walking, running, cycling and others. Temporal biases have been also documented during (and sometimes after) these physical activities. For example, Lambourne et al. measured perceived duration of visual stimuli while cycling, showing a robust overestimation, compared to a rest condition⁷. Similarly, Goudini et al.⁸ measured time perception by asking participants to estimate intervals of 5, 10, 20, and 30 s either before, or immediately, six minutes, or 30 min after the end of a cycling session. The results showed that physical fatigue led to a consistent underestimation of time when the temporal task was performed either immediately after the exercise or six minutes later. A significant effect of physical exercise on time perception has also been reported by Tonelli et al.⁹ within the sub-seconds range (between 200 and 800 ms). Importantly, in this case physical activity was observed to induce a robust overestimation of perceived time with such a bias that persisted for minutes after the end of the cycling session. While these (and many other) studies clearly demonstrated a tight link between physical effort and time perception, the mechanisms beyond these timing distortions are still largely unknown.

In the current study we explored the mechanisms subtending a time distortion phenomenon recently observed during running. In two previous studies, we found that while running on a treadmill (at ~80% of maximal heart rate), the perceived duration of both visual and auditory stimuli (flashes and tones) in the seconds (1 to 4 secs) as well as the milliseconds range (0.2 to 0.8 secs), were overestimated^{10,11}. Despite demonstrating a generalized effects of running on time perception, both studies left open a fundamental question of whether these distortions originate from physiological or cognitive alterations.

Physical exercise (including running) clearly alters many physiological parameters including heart rate, body temperature, muscle activation and it induces the release of specific neurotransmitters such as catecholamine and cortisol¹², both demonstrated to be involved in timing processes^{13–15}. One or more of these physiological alterations, induced by the physical activity, could reasonably explain the many temporal biases observed during physical exercise, including that found while running. However, at odd with a “physiological” explanation, we

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found that the time overestimation bias observed while running, disappear immediately after the running phase ends, even though many physiological variables (such as heart rate) were still altered compared to the baseline level¹⁰. Moreover, the increase of heart rate induced by running (an index of physical effort), compared to a rest condition, was not correlated with the timing bias magnitude¹¹. We interpreted these results as a cue for a non-physiological nature of the effect of running on time perception.

If not driven by physiological changes, what accounts for this effect? While it is evident that running alters physiological variables, it might also alter cognitive processes. Specifically, running could deplete the cognitive resources for the perceptual task as they are needed to plan, execute and control the motor routine. Moreover, while running could be considered a relatively common and automatized motor routine, probably requiring not much cognitive control, this might not be the case in laboratory settings, where participants run on a treadmill. This is an unusual motor routine for many, requiring a precise control of the motor pattern to maintain the position on the continuously moving platform. There is evidence suggesting that even simply walking on a treadmill requires substantial cognitive control. For example, Wang and collaborators¹⁶ administered a colour-words Stoop task to a sample of participants, then selected two sub-samples based on their performance: those performing very well (the top 15 participants, High Attentional Control) and those performing relatively worse (lower 15 participants, Low Attentional Control). The two groups were then required to walk on a treadmill while (dual task) or not (single task) simultaneously performing a 2-back working memory task. The results showed that both cognitive (working memory task) and motor (walking parameters such as step width, gait cycle, step time, forefoot contact times and others) performance deteriorates in the dual task condition compared to the single task, especially in the group with lower attentional control. In line with this, it might be expected that unusual walking patterns (e.g. backward walking), may require additional cognitive resources. Viggiano and colleagues¹⁷ measured attentional performances with a go-no-task in children with and without a diagnosis of ADHD before and after a training protocol based on a walking backward procedure (walking straight at a self-selected comfortable speed over a delimited 10-m pathway for 10 min, thrice a week, for two months). After the motor training, the group with ADHD substantially reduced the number of impulsive reactions, errors (pressure on No-Go signal) and reaction time suggesting that the training phase of walking backward elicited an increase of attentional control. Similar evidence has been gathered by leveraging on dual task paradigms. Castellotti and coll.¹⁸ investigated the effect of several secondary tasks (e.g. read or solve mathematical operations) on time perception. To test the role of physical effort, participants performed the tasks either at rest or while walking. The results showed that more demanding secondary tasks led to larger underestimation errors, suggesting a role of cognitive load. Importantly, the underestimation effects were more pronounced when the tasks were performed while walking compared to the rest condition, suggesting that the motor routine also required attentional resources (see also¹⁹ for a review on cognitive motor interference while walking). Considering these elements, it is plausible that in studies examining the impact of motor routines on time perception, the motor activity may have inadvertently acted as a 'distractor task', diverting cognitive resources away from the time perception task and thus introducing a bias in the encoding of stimuli duration (see Behm & Carter²⁰ for a similar account). It is worth noting that such "attentional" explanation could easily account for time perception being distorted while running but not immediately after the running phase, when the cognitive control required for the motor routine ceased¹⁰. Such potential "attentional restoration" occurring at the end of the task would nicely complement with the energy capacity perspective of sustained attention, according to which, in sustained tasks the volume of cognitive resources decreased over time but they get restored by breaks^{21,22}. In other words, stopping the running activity may allow the perceptual system to reallocate cognitive resources that were previously engaged in motor control, thereby attenuating—or even eliminating—the overestimation bias once the motor activity concludes. A large amount of evidence is showing that attention is implicated in time perception, most of it coming from experiments entailing dual task procedures (e.g.^{23–28}). For example, Rammsayer & Ulrich²⁹ measured time perception by mean of an auditory discrimination task (which longer?) with participants that also performed or not (dual vs single task) a nontemporal secondary task (mental arithmetic). The results indicated that the secondary task substantially decreased the performance in the temporal discrimination task (higher response variability). Interestingly, the cost of the secondary task was similar across different stimuli duration belonging to the sub- or second ranges (around 100 ms or 1 s). There is a long standing debate about whether the perception of durations shorter or longer than a second recruits separate mechanisms with some evidence supporting a dissociation^{15,30–33} and other pointing to common mechanisms^{34,35}. Although this issue has not been definitively resolved (this is also beyond the scope of the current study), it is interesting to note that the results of Rammsayer and Ulrich align with an attentional account of running's effect on time perception. Indeed, in line with our previous findings (see¹¹) their results revealed a qualitatively and quantitatively similar effect of running for durations below and above one second. Besides the psychophysical data, mostly collected with dual task paradigms, there is also clinical evidence supporting a tight connection between attention and time perception. For example, two meta-analysis^{36,37} show significant deficits in time perception children and adolescents with attentional deficit (ADHD) that showed a lower accuracy and precision in processing intervals regardless of the sensory modality of the stimuli—whether visual or auditory.

Finally, theoretical models of time perception often emphasized the role of attention. For example, Zakay and Block proposed an attentional-gate model of timing^{38,39} in which the key feature is a gate controlled by the allocation of attentional resources: the more the attention deployed to the temporal task, the larger the "gate" would open to let more ticks from the internal clock to get collected. As more pulses would correspond to a longer perceived time, the attentional gate hypothesis fully account for the effects of attention on perceived duration in both, the sub and supra second ranges.

To summarize, there is a large amount of evidence suggesting that time perception depends both on cognitive control and motor activity. In the current study, we used an approach similar to Rammsayer & Ulrich²⁹ to investigate the effect of cognitive and physical non-temporal secondary tasks on visual temporal processing

by mean of a within-subjects design. To this aim, we asked participants to perform a temporal generalization task under four conditions: standing still on a treadmill (baseline), running forward, walking backward, or standing still while performing a concurrent secondary perceptual task. As a previous study reported that running affects similarly the perception of time in the sub or supra second range¹¹, to the aim of minimising the number of conditions, we only tested here supra-second durations (1–4 secs). In case the overestimation of visual time observed while running^{10,11} is independent from physical effort but related to the deprivation of cognitive resources, a similar overestimation bias should emerge in all tested conditions (while running, walking backwards and standing still performing a dual-task). Indeed, while these clearly differed for physical effort, they all involved a relatively high cognitive effort (compared to the baseline). On the contrary, in the case the physiological alterations induced by the physical activity are necessary to elicit the observed timing bias, the temporal bias should predominantly emerge in the condition including the running routine. To anticipate the results, we found clear evidence in favour of a cognitive nature of the timing bias.

Materials and methods

Participants

An a priori power analysis based on the results obtained by Petrizzo et al.¹¹ suggested a required sample size of 21 participants (two-tail t-test for two dependent means, $\alpha=0.05$, $(1-\beta)=0.9$).

A total of 22 participants with normal or corrected-to-normal vision participated in the study (1 author, 21 naïve, 10 females, mean age = 26, SD = 4.9). With a pre-test qualitative survey, we assessed the participants' sports habits. Ten participants reported no sporting activity at all. Two participants were involved in competitive sports (one football player and one football referee). All the other participants were engaged in different non-competitive activities (gym: four participants, running: three participants, volleyball: one participant, indoor climbing: one participant, boxing: one participant). A medical certificate of good health (even non-competitive) was required for the participation in the study. The overall experiment lasted about 2 h per participant, with the temporal order of experimental conditions (described below) pseudo-randomized across the participants (Baseline was administered 6, 7, 3 and 6 times as the 1st, 2nd, 3rd and 4th condition respectively; Walking Backward 6, 5, 6, 5 times as the 1st, 2nd, 3rd and 4th condition; Running: 6, 4, 5, 7 times as the 1st, 2nd, 3rd and 4th condition and Dual task: 4, 6, 8, 4 as the 1st, 2nd, 3rd and 4th condition). Most of participants (N13/22) completed the experiment within the same day, the others (N9/22), due to logistical reasons, were tested in two separate but consecutive days (usually two conditions were performed at day 1 and two at day 2). The research was approved by the local ethics committee ("*Commissione per l'Etica della Ricerca*", University of Florence, 7 July 2020, n.111). All participants provided written informed consent, and all the experiments were conducted in accordance with the Declaration of Helsinki.

Apparatus and stimuli

In separate conditions, participants were standing still, running, or walking backwards on a treadmill (JK Fitness Top Performa 186), in a dimly lit and quiet room at approximately 90 cm from a monitor (Telefunken Smart TV 43"). Heart rate was monitored with a Garmin Forerunner 55 smartwatch paired with an HRM-Dual Heart rate strap.

Following our previous experiments^{10,11}, duration intervals were marked by the a centrally displayed blue square (subtending an area of approximately $15^\circ \times 15^\circ$ at the viewing distance of 90 cm). In the dual-task condition, coloured square stimuli ($1.5^\circ \times 1.5^\circ$) were also centrally and briefly (250 ms) presented, after and before the duration stimulus (similar to⁴⁰, see Fig. 1). In all the conditions, participants judged the duration of the test stimulus (same-different duration) compared to an internalized reference fixed duration of 2 s. The test durations were logarithmically spaced around the reference stimulus, with a constant difference between successive durations of approximately 25%: 1.002, 1.262, 1.589, 2, 2.518, 3.170, and 3.990 s.

Stimuli were generated and presented with PsychToolbox 3 routines in Matlab 2016b (The MathWorks, Inc., Natick, MA, USA, <https://www.mathworks.com/products/matlab.html>)^{41–43}.

General procedure

Time perception for visual stimuli was measured with a time generalization, same-different task, as that used in our previous experiments^{10,11}. A schematic representation of the procedure is depicted in Fig. 1. Before the experiment, participants were familiarized with the task by a training procedure in which the 2 s visual reference stimulus was repeated sequentially five times with no response required and participants required to memorize its duration. This sequence was then followed by a block of seven test trials each one testing one of the possible durations (randomly presented once). In this case participants were required to judge whether the stimulus duration was the same or different compared to that previously learned. In this phase we provided response feedback by a colour change of the central fixation point: green for correct responses, red for mistakes. After this block of seven trials, the percentage of correct responses was computed. If accuracy rate was at least 85%, the training ended, while it continued with an additional seven-trial blocks until participants achieved the 85% accuracy criteria.

Following training, participants performed the temporal generalization task either standing still on the treadmill (baseline), or while running, or while walking backwards or standing still and performing a secondary visuospatial task. As fatigue could influence performance (particularly in physically demanding conditions) after each block of running and backward walking, participants rested until their heart rate returned to baseline levels (roughly 15 min) before continuing with the experiment. In all the cases, the task started with an "encoding phase" in which the reference stimulus was again presented five times consecutively with participants asked to passively observe the stimulus and memorize its duration. This phase was followed by a 3-minute "consolidation phase", in which no stimulus was presented. Subsequently, the "decoding phase" started. On

Temporal generalization task

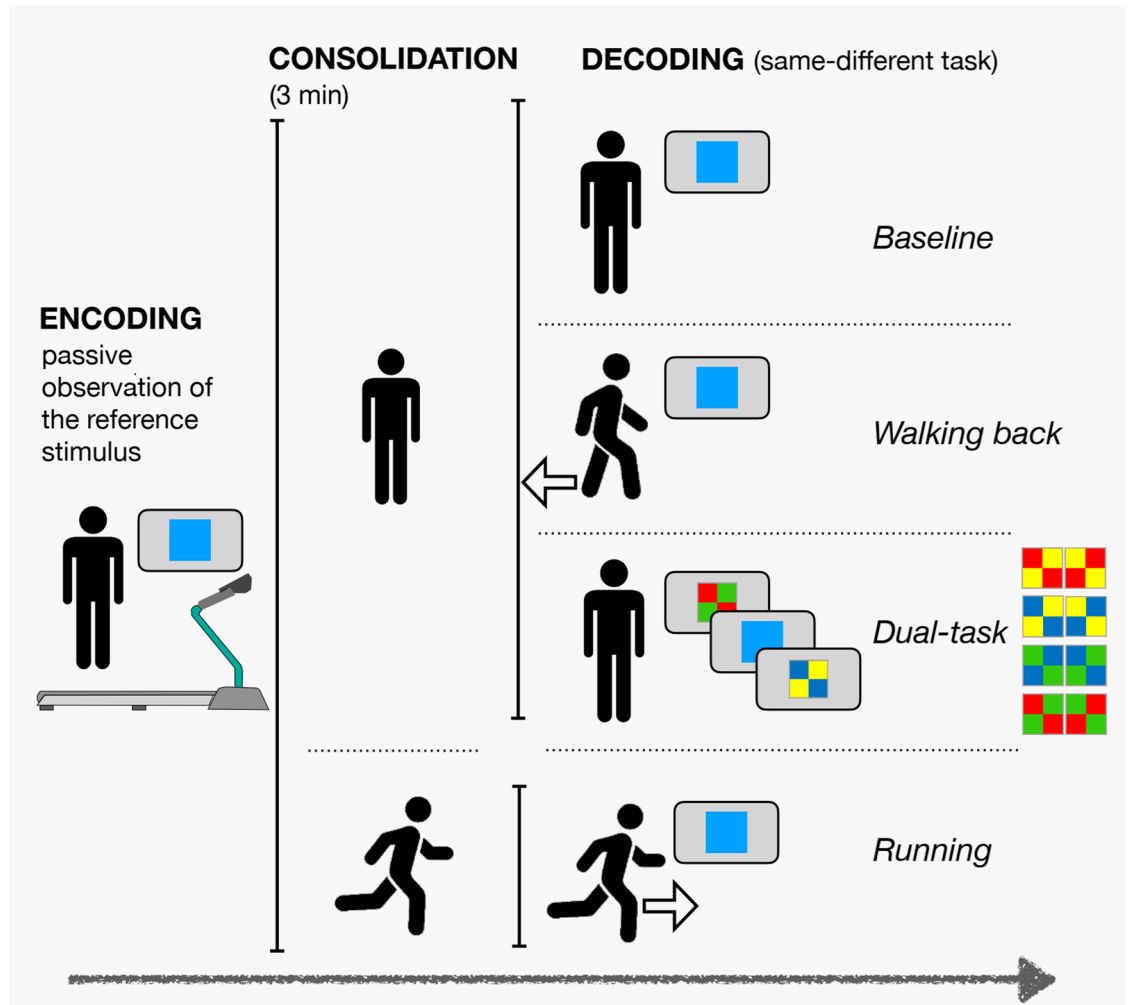


Fig. 1. Schematic representation of the paradigm. In the encoding phase, participants were presented with a reference visual stimulus (a blue square) lasting 2 s displayed for five times consecutively and they were required to memorize that duration. This phase was followed by a 3 min without any visual stimulation (consolidation). After this phase, the decoding start with participants judging whether a visual stimulus (with variable durations ranging from 1 to 4 s) lasted the same, or a different amount of time compared to the memorized 2s reference (same-different task). The decoding phase (in different sessions) was performed while standing still with all the cognitive resources available for the temporal task (baseline), while walking backwards, while standing still but executing a concurrent additional visuospatial task (dual task) or while running. The duration of the decoding phase was approximately 5 min for the baseline, running, and backward walking conditions, and about 8 min for the dual-task condition (due to the additional time required for the presentation of “distracting” stimuli and response recording in the concurrent visuospatial task).

each trial a test duration was presented, and participants were asked to verbally indicate whether the stimulus lasted the same or different amount of time compared to the reference (same-different task). The experimenter, blind to the stimuli, recorded the response with the appropriate key press. In the “decoding phase”, the stimulus with the duration identical to the reference (2 s) was presented 18 times while the remaining 6 stimuli (those with different durations than the reference) were presented 6 times each, for a total of 54 trials. Each stimulus duration was randomly selected trial-by-trial. The oversampling of the 2 s duration (same stimulus) had the aim to accurately measure the Point of Subjective Equality (see later for details). In every experimental condition, the entire encoding – consolidation – decoding procedure was performed twice in two consecutive blocks, for a total of 108 trials per condition.

Experimental conditions

In all the experimental conditions, the encoding phase (described above) was performed standing still on the treadmill. In the “baseline” condition, participants also performed the consolidation and decoding phase while standing still. The dual task condition was identical to the baseline with the exception that in ‘decoding phase’, two checkerboard squares stimuli were also presented, one before and one after the duration stimulus (each randomly selected trial-by-trial among eight possible colour configurations, see Fig. 1). After this three-stimuli sequence, participants were first asked to verbally judge whether the checkerboard squares stimuli had the same colour pattern (visual working memory task) and then to indicate whether the duration stimulus (the blue square) was equal or different compared to the 2 s learned reference.

In the backward walking condition (as in the baseline and dual task) participants performed the “consolidation phase” standing still on the treadmill but, after this phase, participants start walking backward on the treadmill, and the ‘decoding phase’ started. The treadmill speed was set to a fixed value of 4 km/h. This speed was selected by preliminary tests to be comfortable as participants were instructed not to lean on the treadmill arms unless they felt they were losing their balance. Heart rate was recorded throughout the entire walking period.

In the running condition, only the encoding phase was performed while standing still. At the end of the encoding phase, participants started running. Following the same procedure adopted by Petrizzo et al.^{10,11}, the treadmill speed was adjusted ad-hoc for each participant to achieve, within 3 min, a pre-defined heart rate corresponding to 80% of the maximum heart rate calculated using the formula: $208 - (0.7 \times \text{age})$ ⁴⁴. Subsequently, the timing task started, while participants kept running and lasted approximately 5 min (with the total running time for each block lasting about 8 min). During this phase, the treadmill speed was dynamically adjusted by the experimenter (if necessary) to maintain participants’ heart rate around the target (80% of the maximum heart rate). Between the first and the second block of trials participants were allowed to take a few minutes break.

Data analysis

Timing data were analysed as in Petrizzo et al. (2022, 2023). The proportion of “same duration” responses were plotted as a function of the test duration and fitted with a Gaussian function. For all the Gaussian fits (on the individual data), an $R^2 > 0.8$ was achieved. The peak of the fits describing the data distributions reflects the point of subjective equality of test and reference (PSE): the duration of the test stimulus being perceived to be the same as the reference stimulus. The standard deviation of the Gaussian fits was used as a measure of sensory precision. Both PSEs and SDs were normally distributed (Shapiro Wilk $p > 0.05$). The magnitude of the temporal distortions induced by running, walking backward and dual task was indexes as the standardized difference from the PSEs recorded at baseline (Eq. 1).

$$\text{Normalized effect} = 100 * \frac{PSE(\text{expcond}) - PSE(\text{bas})}{PSE(\text{expcond}) + PSE(\text{bas})} \quad (1)$$

where PSE (exp condition) and PSE (bas) reflect the PSE measured in each experimental condition (running, walking backward, dual task) or in the baseline (rest) condition, respectively.

To statistically quantify the effects on accuracy and precision, PSEs and SDs were analysed by repeated-measures ANOVAs. Post-hoc tests were performed by t-test with p values (two-tailed) corrected for multiple comparisons (Bonferroni–Holm method). As the effect of running and walking backward (as measured by Eq. 1) violated normality (Shapiro Wilk $p < 0.05$), we used nonparametric statistics (Kendall’s Tau) to measure the correlations between the effects. Effects size has been reported as Cohen d and frequentist post-hoc t-test and correlations were also complemented with the estimation of Bayes Factors⁴⁵, which quantify the evidence for or against the null hypothesis (as the ratio of the likelihoods for the alternative and the null hypothesis). We express Bayes Factors as the base10 logarithm of the ratio ($\text{Log}_{10} \text{Bf}_{10}$), where negative values indicate that the null hypothesis is likely to be true, positive that it is false. By convention, absolute Log_{10} Bayes Factors between 0 and 0.47 are considered anecdotal evidence, from 0.47 to 1 moderate evidence, from 1 to 1.5 strong evidence and greater than 1.5 very strong evidence.

In the dual-task condition, to analyse only the trials in which participants paid attention to the distractor task, we discarded the trials in which participants provided an incorrect response to the distractor task (218 trials in total, average proportion of correct response: 91%; min 78%, max 98%).

Data were analysed by JASP (Version 0.19.1) and Matlab software. Matlab was used to fit the timing data with Gaussian functions, and to estimate PSEs and SDs. JASP was used for all the other statistical tests. The power analysis to define the required sample size was performed by G*power software (Version 3.1.9.6).

Results

Using a temporal generalization task, we asked participants to compare the duration of visual stimuli (ranging from 1 to 4 s) to the duration of an internalized visual reference (lasting 2 s). Participants completed the task under two static (baseline, dual task) and two active (running, walking backward) conditions. In these latter conditions, physical effort was indexed by heart rate, while in the baseline and dual-task conditions, the heart rate was only registered with a 1-min recording before the encoding phase (Fig. 2).

Figure 3 shows the results obtained in the timing task, pooling all the data together (across participants). On each panel, the red curve reports the data obtained in the baseline condition while the other curves report the data obtained while running (A, blue), walking backwards (B, grey) and in the dual task condition (C, green). On visual inspection, it is evident that all the curves were similarly shifted leftward relative to the baseline, indicating a time overestimation. In the baseline, the peak of the Gaussian function (PSE) was near to the physical reference duration (2.023 s), indicating that participants were fully capable to perform the task. In the running condition (A), a stimulus lasting 1.807 s was perceptually judged as equivalent to the 2 s reference,

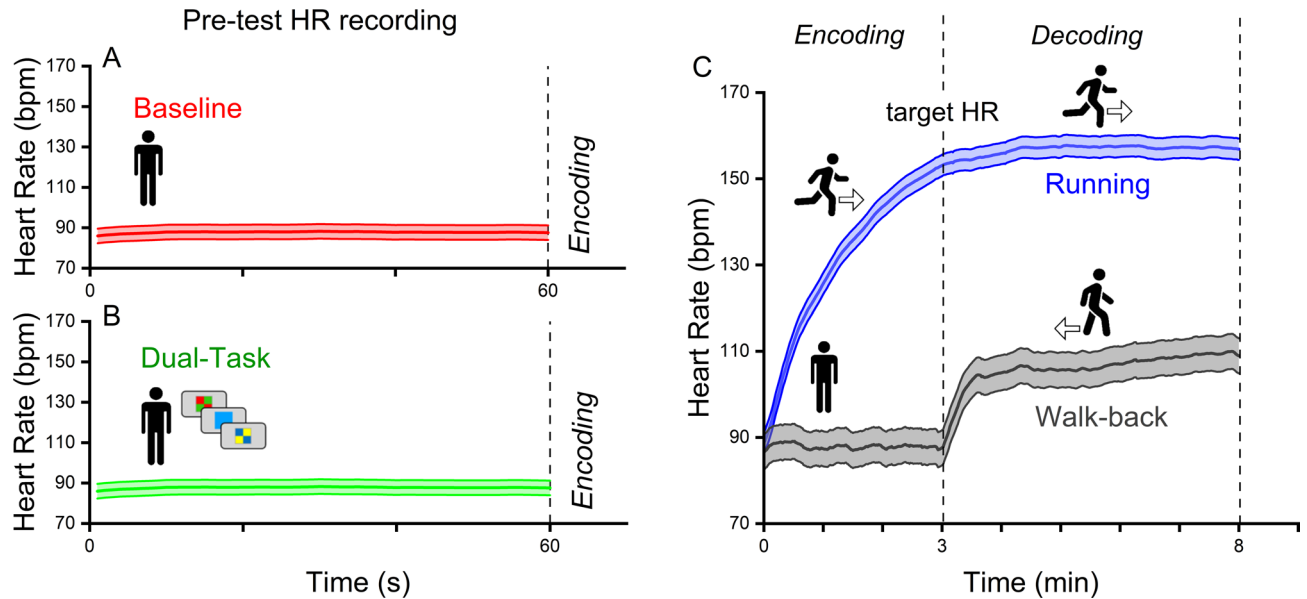


Fig. 2. Heart rate. Between participants average heart rate (bold lines) and relative confidence interval (95%, shaded areas) measured as beats per minute (bpm) in the different conditions: baseline (A, red), Dual-Task (B, green), running and walking backward (C, blue and grey respectively).

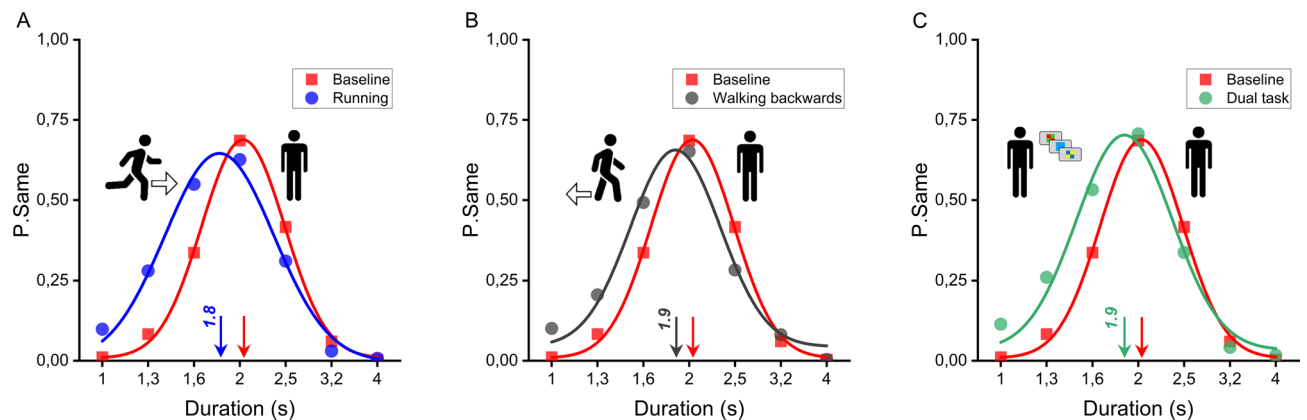


Fig. 3. Aggregate results. Proportion of “same” responses against test stimuli durations with the corresponding fitted Gaussian functions. Red curves in each panel indicate data for the baseline condition shown along with data obtained while running (A, blue curve), walking backwards (B, grey curve) and in the dual task condition performed while standing (C, green curve). The peaks of the fits (indicated by the arrows) correspond to the point of subjective equality (PSEs). The duration of the standard stimulus was 2 s. All curves were leftward shifted compared to the baseline, indicating an overestimation of the visual stimuli perceived while running (A), walking backwards (B) and while performing a concurrent visual working memory task at rest (C).

indicating an overestimation of about 190 ms (~9%). Similar results were observed in the other conditions. The PSE in the backward walking (B) and dual-task conditions (C), were 1.860 s and 1.851 s respectively, indicating an overestimation of approximately 7%.

The same analysis was also performed on individual data. Figure 4 A shows the individual PSEs measured in the baseline condition against those measured while running (blue), walking backwards (grey) and in the dual task condition (performed at rest, green). Despite large individual differences, most of the data points fall under the diagonal, regardless of the condition to confirm that a similar overestimation bias was observed in all conditions.

A repeated measures ANOVA on PSEs (4 conditions: baseline, running, walking backwards, dual task) revealed a significant main effect of condition ($F(3, 63) = 5.812, p = 0.001$), confirming that (overall) the physical/cognitive manipulations had an effect on perceived duration. To test the relative contributions of each experimental condition, we ran post hoc *t*-tests. The results show significant differences between the “baseline” and the all the other conditions: “running” ($t = 5.08, p_{\text{holm}} < 0.001, \text{Cohen } d = 0.930, \text{LBF} = 2.7$), “walking

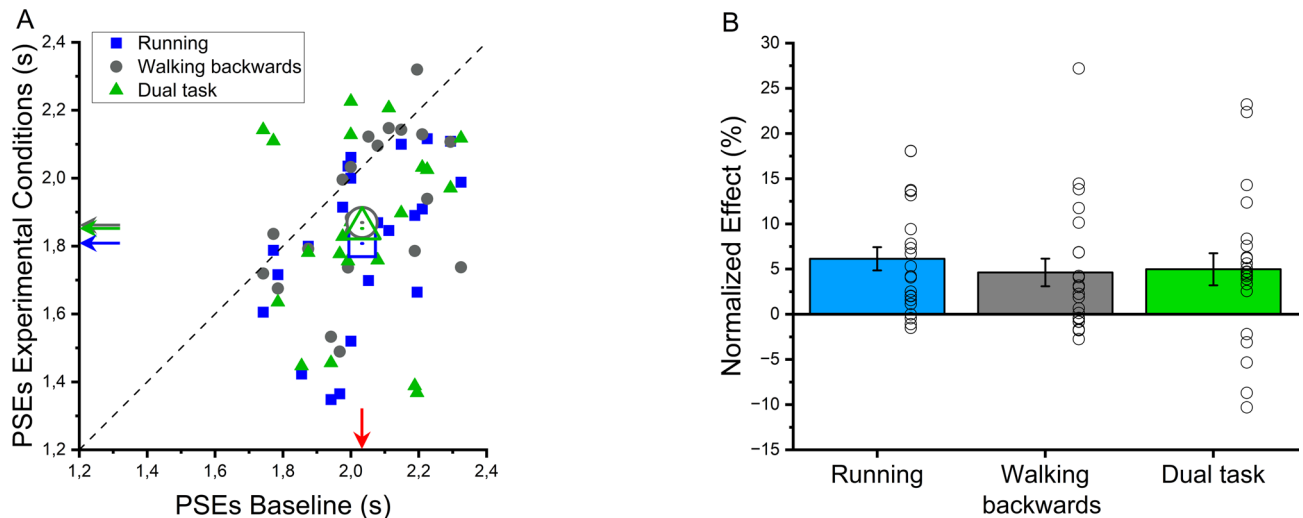


Fig. 4. Individual Points of Subjective Equality (PSEs). **(A)** Visual time PSEs measured while running (blue squares), walking backwards (grey circles) and in the dual task condition (green triangles) against PSEs measured at baseline. Big symbols and arrows report between participant's average. **(B)** Normalized time overestimation effect (Eq. 1) measured while running, walking backwards or while performing the timing task while standing but with deprived attentional resources (same colour conventions as A). Error bars report ± 1 sem.

backwards" ($t=3.203$, $p_{\text{holm}}=0.021$, Cohen $d=0.676$, LBF=1) and "dual task" ($t=2.784$, $p_{\text{holm}}=0.045$, Cohen $d=0.746$, LBF=0.66). All the other comparisons were far from significant differences, confirming similar effects (walking backwards Vs running, LBF = -0.39; walking backwards Vs dual task, LBF = -0.65; running Vs dual task, LBF = -0.55, all $p_{\text{holm}} > 0.75$). Since some participants performed the experiment in two sessions on separate days while others completed the whole experiment in the same day (see methods), we reanalysed the data by including the day of testing (1 or 2) as a between subjects' factor. The results remained virtually identical with a main effect of condition ($F(3, 60)=5.309$, $p=0.003$) and no interaction between day of testing and condition ($F(3, 60)=1.405$, $p=0.23$). Post hoc t -tests confirmed significant differences between the "baseline" and the all the other conditions: "running" ($t=4.83$, $p_{\text{holm}} < 0.001$, LBF=2.7), "walking backwards" ($t=3.01$, $p_{\text{holm}}=0.03$, LBF=1) and "dual task" ($t=2.67$, $p_{\text{holm}}=0.05$, LBF=0.65) with the other comparisons providing similar effects (walking backwards Vs running, LBF = -0.4; walking backwards Vs dual task, LBF = -0.55; running Vs dual task, LBF = -0.65, all $p_{\text{holm}} > 0.6$).

To better visualize the data, Fig. 4 B shows the normalized effects (against baseline), confirming a large individual variability but also rather similar average overestimation biases (positive values).

As in our previous study¹¹, we also looked at correlations between heart rate modulation (an index of psychical effort) and the magnitude of the temporal biases found while running and walking backwards. We quantified heart rate modulation (for each participant) as the difference between the heart rate measured at rest (see Methods) and the average heart rate recorded during running (excluding the first three minutes required to reach the heart rate threshold; see Methods) or walking backwards. The average heart rate modulations were 69.17 and 19.10 beats per minute for the running and walking backwards, respectively. Confirming previous evidence¹¹, we found no correlations between heart rate modulation and the magnitude of temporal bias (running: $\tau=0.03$, $p=0.82$, LBF = -0.15, walking backwards: $\tau=0.1$, $p=0.53$, LBF = -0.55).

We then explored the possibility of shared resources driving the effects observed in the different conditions. To this aim we correlated the effect's magnitudes across conditions under the assumption that the use of shared resources would provide positive correlations. Partially in line with this possibility, the results show positive, but weak, correlations between the three effects (Running Vs Dual task: $\tau=0.31$, $p=0.04$, LBF=0.26; Walking Vs Dual task: $\tau=0.25$, $p=0.1$, LBF=0; Walking Vs Running: $\tau=0.22$, $p=0.16$, LBF = -0.14).

Finally, to assess the timing tasks difficulty under the different conditions, we analysed sensory precision (standard deviation of the Gaussian curves describing the data, see methods). In the baseline condition the average SD was 0.083, slightly lower (higher precision) compared to the other conditions (running=0.1, walking backwards=0.093, dual task=0.094). A repeated measures ANOVA on SD (four conditions: baseline, running, walking backwards, dual task) provides no evidence for a main effect ($F(3, 63)=1.719$, $p=0.172$), suggesting similar precision levels between conditions (Fig. 5).

Discussion

We recently reported that visual and auditory stimuli are perceived as lasting longer while running on a treadmill^{10,11}. Importantly, the temporal bias disappeared immediately after the end of the running phase, suggesting that the effect might originate from factors unrelated to physiological alterations as these usually require much more time to revert to a baseline level. Here we tested an alternative possibility according to

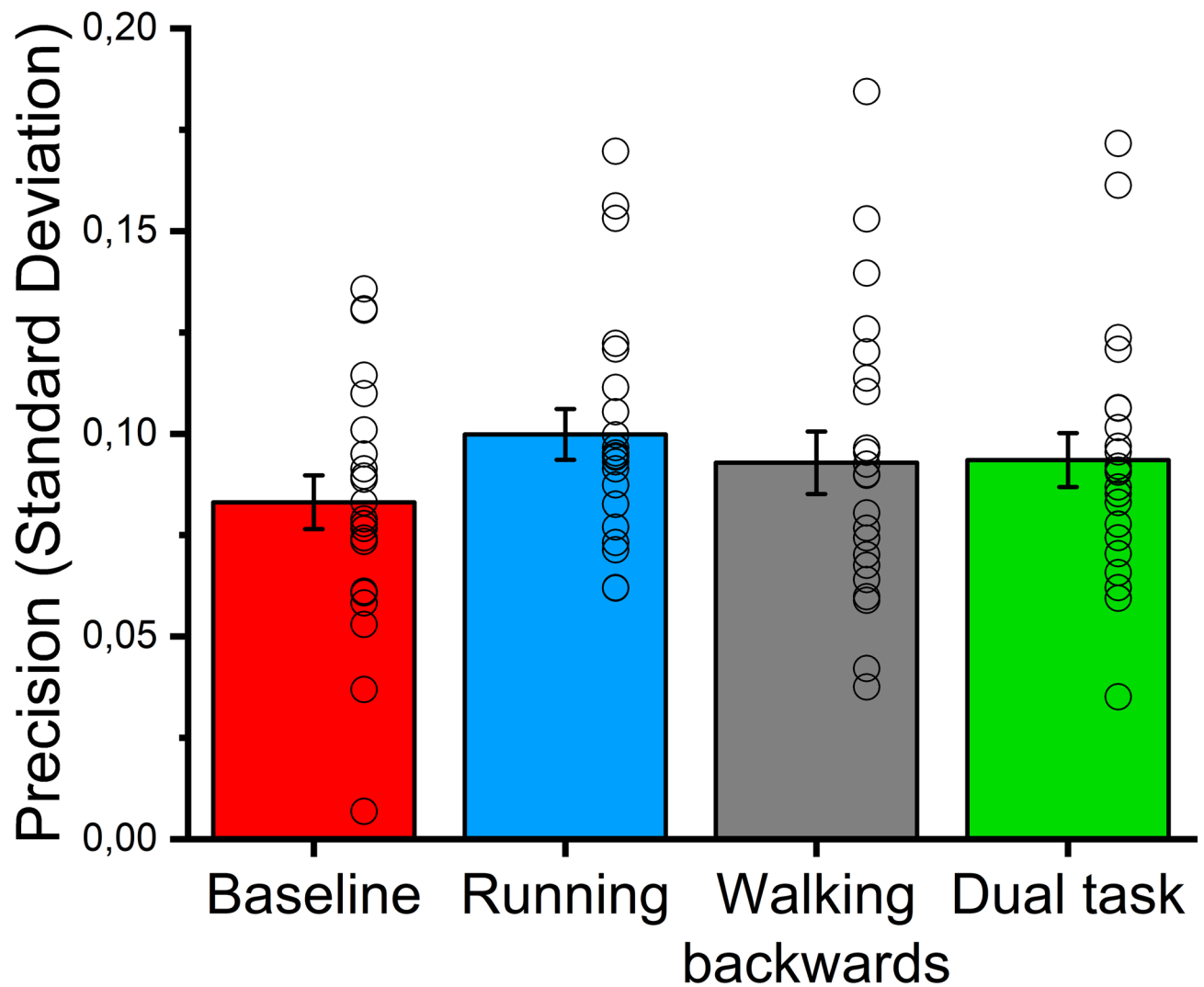


Fig. 5. Sensory precision. Standard deviation of the Gaussian curves describing the time estimates for the four different experimental conditions (baseline: red, while running: blue, while walking backwards: grey and dual task: green triangles). Bars reports between participants average, symbols single subject data and error bars ± 1 sem.

which the running routine might have acted as a distractor task, depleting the cognitive resources available for accurately judging sensory time, thus distorting its estimation. To test this “cognitive” possibility, we compared the effect of running on visual time perception, to that obtained in other two conditions requiring significantly less physical effort but both involving cognitive effort. In these conditions, participants performed the timing task either while walking backwards or while standing still but with their cognitive resources divided between the timing task and a concurrent visual-working memory distractor task. In line with the possibility that the perceptual time overestimation observed while running originates from cognitive rather than physiological factors, we found that both walking backwards, and dual task (performed at rest) induced a very similar effect as that provide by the running routine. In other words, given that our experimental conditions strongly differed in terms of physical effort but were all designed to require a relatively high amount of cognitive control, our results seem to suggest that the effect of running on time perception is likely mediated via cognitive resources. The current results are in line the Zakay and Block attentional gate model of timing^{38,39}. The model suggests that the more attention is allocated to time, the longer the duration is perceived. It can be speculated that in the divided attention conditions, compared to the single task, participants allocated relatively more attention to the timing task. This strategy could have been employed to maintain a good level of performance in the temporal task under distracting conditions. According to the attentional gate model of timing this would have resulted in a wider or more frequent opening of the gate, leaving more pulses entering in the mechanism, finally resulting in a temporal overestimation of the visual stimuli. The potential use of this strategy aimed at ‘saving’ the duration task appears to be consistent with the data obtained for the second performance parameter measured, precision. The result showed that running, walking backwards and the dual task conditions were all not able to deteriorate timing sensory precision, compared to the baseline. This could have happened because the participants, in these

conditions, prioritised the timing task. Beyond this possibility the results about precision also suggest that the effects found on the accuracy of time estimates (PSEs) do not stem from differences in the difficulty of the different conditions and fit well with previous evidence showing different effects of physical exercise on time precision and accuracy⁴⁶.

In this experiment we indexed physical effort by heart rate. During the backward walk, the average heart rate was around 106 bpm, only 19 bpm higher compared to a resting state (87 bpm, 20% increase on average). During running, on the other hand, the average heart rate was around 156 bpm, 80% higher compared to rest. In other words, although running induced a fourfold increase in heart rate compared to walking backwards, the effect on time perception was virtually identical. Unfortunately, in the dual task, we measured heart rate only before the start of the timing task and thus we cannot say much about the rate of increase induced by the dual task itself. However, previous evidence shows no heart rate modulation while performing a color–word Stroop task at rest⁸, in line with the idea that the temporal bias observed here originates from the cognitive effort induced by the divided cognitive resources rather than a possible increase in heart rate. Congruently with this, walking backwards has been demonstrated as an attentional demanding motor task¹⁷, probably acting here as a distractor activity and indeed producing a very similar timing bias compared to the “static” dual task condition.

While the overall pattern of results points toward a cognitive explanation of the effect, there is another possibility. Even though walking induces a weak physical effort compared to the running condition, it could still be sufficient to induce the observed temporal bias. Moreover, the effect found while walking backwards could be already at a ceiling level and therefore difficult to be further increased by the extra physical effort required by running. Although we cannot completely rule out this possibility, it nevertheless seems unlikely as we found the very same temporal overestimation effect even when standing still but performing the temporal task with the cognitive resources reduced by a concurrent visual distractor task. However, one could still argue that this attentional effect, despite being qualitatively and quantitatively like that induced by running and walking, could derive from the use of different mechanisms. To check for this possibility, we ran a correlation analysis between the effects measured in the three experimental conditions. The analysis showed positive trends, but the strength of the correlations was weak. Even if it is difficult to draw firm conclusions bases on null to weak correlations, the analyses suggest the use of similar but probably not fully shared resources.

The current study has limitations. Given that we examined only one type of physical activity (running), only one perceptual feature (time) by using a single experimental paradigm (temporal generalization task), future investigations are needed to test whether and to what extent the pattern of results found here can be generalized to other actions, sensory inputs and methodologies. Another limit of the current study is the lack of investigation of the potential dynamic development of the timing bias described here. It could indeed be postulated that, if the bias is cognitive in nature (as we are arguing), we might expect a temporal evolution of the effect along the trials. Indeed it has been showed that while performing a sustained task, cognitive effort⁴⁷, attentional capacities and performance actually fluctuate over time²¹. However, as the experimental paradigm exploited here did not allow us to make any quantitative estimate of these fluctuations, we have to leave this issue open for future investigations. A similar issue comes if we would leverage on the dynamic allocation of attentional resources between the primary and secondary tasks by looking at the performance variability over time, even at a trial – by – trial base. Again, the exploited technique does not allow us to do so as it requires many trials to obtain a reliable fitting of the data and thus reliable estimates of perceived duration. In other words, the design of the experimental methods does not allow to perform such analysis, but it will certainly be an important issue for future research aimed at investigation the role of cognitive resources in eliciting perceptual biases. Another potential limitation of this study, that is worth to be considered, regards the way participants had to build up a reference for temporal estimates. All our experimental conditions included an encoding phase with five initial reference trials to learn and remember the 2 – second standard stimulus to accomplish before the following the test trials (decoding). As the internal standard could drift over trials⁴⁸, having only this initial reference block could be methodologically suboptimal. However, a carry-over effect seems unlikely as in the baseline condition, we observed no bias, suggesting that even in the case of carry over or drift effects, they are unlikely to affect the performance in a specific direction (under vs overestimation). Moreover, since the same procedure was applied in all experimental conditions, any potential carry over effects would have been equally present in all the cases, making the comparisons between conditions still meaningful. Another methodological issue that is worth to be considered is that the running condition was the only one in which the consolidation phase was performed while running. Indeed, in all the other conditions it was performed at rest. We opted for this experimental design as we aimed to keep the time interval between the end of the consolidation phase and the beginning of the decoding phase constant across conditions. At the same time, we also aimed to start the decoding phase only when each participant had reached a predetermined heart rate threshold (80% of their maximum), to standardize the physical effort across participants as much as possible. We acknowledge that this choice introduced an asymmetry between conditions with this, in turn, that might potentially have influenced the results. However, it is worth noting that the findings revealed very similar effects across conditions, despite the presence of such asymmetry, to suggest that it did not significantly affect the reported results.

In conclusion, despite the limitations mentioned above, the results of the current study suggest that we should be very cautious in interpreting perceptual timing biases observed during physical activities as reflecting physiological alterations. The results also encourage the scientific community investigating time perception in ecological sensorimotor contexts to consider the potential confounding role of cognitive factors implicated in the execution of complex motor routines.

Data availability

Data are available upon request to the corresponding author.

Received: 18 March 2025; Accepted: 17 June 2025

Published online: 15 July 2025

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Author contributions

T.B. I.P. R.A. G.A. contributed to designing the experiments and writing the manuscript; T.B. I.P. also contributed to data acquisition and data analysis.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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