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RESEARCH ARTICLE

Synchronising to a frequency while estimating time of vibro-tactile stimuli

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Abstract
It is well known that subjective time perception can be modified by the emotional experience related to a specific event, by pharmaceutical compounds or by sensory stimuli. As for the latter, visual and auditory stimuli have been widely studied compared to tactile ones. Two experiments were conducted using different vibratory frequencies to stimulate participants who were asked to reproduce stimulus duration. Experiment 1 compared differences in reproduced times for 8-s stimuli ranging between 0.5 and 6 Hz in 100 participants who performed a time reproduction task with the stimulus present or absent during the reproduction. The task was done under prospective and retrospective paradigms. Experiment 2 assessed differences in reproduced times by 80 participants under vibrotactile stimulation of two frequencies simultaneously delivered to each hand, frequencies with specific proportions of 0.5 and 0.75 times the standard frequency for two groups of standard frequency (2 or 12 Hz). Reproduced times in Experiment 1 did not show significant differences among frequencies. Significant differences were found for the absence/presence condition, solely, in prospective tasks, where estimations were longer in the absence of the vibrotactile stimulus. Significant differences were found in Experiment 2 for reproduced time by participants between groups of standard frequency. Data analysis suggests the need to improve the understanding of the subjective time perception processes for higher frequencies considering the intensity modulation based on the amplitude and frequency relation. Results open the possibility of designing new protocols in the study of time perception and other cognitive functions.

Keywords Subjective time · Vibrotactile stimulation · Frequency · Time perception

Introduction

Subjective time is understood in two main concepts: as the sequence of a series of events or as the duration between two successive events (Allan 1979; Fraisse 1984). The perception of both the sequence of events or duration can be similar to objective measures or be distorted (Eagleman 2008). The characteristics of time perception have been studied using mainly five tasks and two timing paradigms. The tasks were verbal estimation, Temporal Order Judgement (TOJ), interval comparison (generalisation and bisection), production and reproduction (Block 1990; Eagleman 2008). These tasks can be performed in two ways, when subjects know they are going to perform a temporal task (prospective timing) or while subjects are naïve to the temporal purpose of the task and they are asked later to estimate a past event (retrospective timing). Based on these methodologies, several models of time perception have arisen.

The internal clock and other neurobiological models have been the dominant models in literature; however, they better describe especially phenomena in the range of milliseconds (Buonomano 2007). The importance of other models which fits better to longer durations has been frequently discussed (Block et al. 2010; Firmino and Bueno 2008; Nather and Bueno 2011; Nather et al. 2013). Hence, for lapses of several seconds it is necessary to consider models that emphasise more complex processes of attention (Block and Gruber 2014), memory (Staddon et al. 1999), cognitive load (Block et al. 2010), expectancy as future-oriented attending in the dynamic attention theory (Jones and Boltz 1989) or as Ornstein (1969) proposed, including non-temporal properties such as complexity or arousal (Treisman et al. 1990).

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Experiments in temporal perception and the models that have arisen from them have usually employed procedures that use visual (e.g. Bueti and Macaluso 2011; Droit-Volet 2003, 2010; Nather and Bueno 2012; Nather et al. 2013), auditory (e.g. Droit-Volet et al. 2010; Firmino and Bueno 2008; Kellaris and Kent 1992; Lakens et al. 2011; Ramos et al. 2011) and just a few, compared with the others, somatosensorial (e.g. Hasuo et al. 2014; Zampini et al. 2005; Khoshnejad et al. 2016) stimuli. These studies related to the tactile system have involved, in general, Temporal Order Judgements tasks and have evaluated motor behaviour in scales of less than a second (Yamamoto and Kitazawa 2016), some of them even evaluated crossmodal interactions (Grondin and Rousseau 1991; Occelli et al. 2011; van Erp and Werkhoven 2004). However, temporal estimation at longer durations or in tasks of explicit estimation of tactile stimulus has been scarcely assessed.

A consequence of the lack of studies regarding time perception in some sensory modalities is that tasks and protocols to asses this process get short-handed because they keep relegated to the use of visual or auditory stimuli.

Khoshnoodi et al. (2008) developed a series of experiments aiming to evaluate the differences and correlations on temporal estimation of participants that were first stimulated (stimulation phase) with several tactile stimuli of 8 s, varying in frequency (from 6 to 48 Hz), and who were then asked to reproduce the stimulus duration (reproduction phase). Some stimuli could include the presence of a gap between two durations. The effects of the gap length (between 0 and 6 s), the gap context (frequencies before and after the gap) and the gap content (oscillation frequency during the gap) were also assessed. Negative correlations were found between estimated time and stimulus frequency; the authors concluded that those correlations supported theories stating that time perception is a function of the amount of working memory allocated to a task rather than the result of modifying the speed of an internal clock (Ivry and Spencer 2004). However, in the tasks, participants had to compare lapses coded under different frequencies presented in sequence. Usually, time reproductions are performed in the absence of the tested stimulus (e.g. Gorea 2011; Nather and Bueno 2011; Nather et al. 2013) that can influence results if one considers that subjects are comparing one interval with high levels of information (in the stimulation phase), in terms of the number of oscillations, to another with a low level or even null information (reproduction phase). Hence, it can be hypothesised that time perception is different in the reproduction phase when a subject performs the reproduction in the absence than in the presence of the stimulus. If one acknowledges that the stimuli affect the way time is perceived, time is being remembered equally in both conditions, but the perception of the ongoing time during the reproduction is different. It was the target of this study to know whether there are differences in the variation in the perception of time between two basic conditions (presence and absence of stimulus during reproduction) and how it is framed on current theoretical models of time perception.

Expanding the scope of possible stimuli modalities allows to design new protocols, in particular, assessing whether the condition of absence or presence of the to-be-timed stimulus during the execution of the task affects the process of time perception. This analysis is helpful in situations in which the stimulus can be presented simultaneously with stimuli of other modalities without having significant crossmodal interactions. And, therefore, this procedure may allow the participant to perform temporal estimation tasks of a stimulus while performing other cognitive tasks involving stimuli of a different sensory modality.

If distortions are due to simple counting rates of an internal clock, we would expect to find specific ratios, a linear variation, between reproduced times (RTs) and frequencies in the condition where the vibration is absent during the reproduction phase, and a tiny or null variation of those ratios among frequencies in the condition where the vibration is present during the reproduction phase (Mattheus and Meck 2016). Rather, displaying another kind of behaviour would point to a mechanism of time perception besides the internal clock model in which time is reconstructed based on a series of cognitive elements.

In the study of time perception, analyses of the effects of stimuli are frequently made in terms of frequency, but there is a related factor that may contribute to the outcome, the relative speed. Kaneko and Murakami (2009) tested this hypothesis discriminating the temporal frequency, spatial frequency and the speed of visual stimuli. In order to achieve that, there was the need for a specific but widely used visual stimulus, a Gabor patch. A series of Gabor patches varying in spatial and temporal frequency was used, and the sinusoid speed arose as a new variable because of the interaction of the two former ones. Kaneko and Murakami (2009) concluded that the speed, rather than solely the spatial frequency or the temporal frequency, was the key factor behind temporal distortions. In visual modality, and using that kind of stimuli, it is easy to assess the effect of sinusoid speed, but it is hard for a subject to extract that characteristic from a vibrating object. The frequency of an oscillation is directly related to the speed of the vibrating object, but the perception of speed depends on the speed of the context (Gorea 2011). Thus, subjects perceive the speed of a target faster near static contexts than with the background moving in the same direction. It is possible to extend such way of thinking to propose an evaluation of relative speed/frequency of some tactile, vibrating stimuli. Therefore, our second objective was to evaluate differences in subjective perception of time while participants were stimulated by two simultaneous vibrations with two specific ratios of frequency.

The main issue herein addressed is related to perceptual processes as there is a lack of studies on tactile stimulation (Ogden et al. 2015), but there is also a lack of studies on the range of frequencies used and the protocols under which participants perform the time reproduction task. Protocols involve the paradigm used and the condition of presence or absence of the stimulus during the reproduction. Even though Motala et al. (2018) used low frequencies in a procedure involving vibrotactile stimuli, their experiment is in the field of motor timing as subjects needed to estimate the interval between a series of vibratory bursts and not estimating the whole duration of the burst's sequence. Henceforth, there is a potential of research on the tactile perception and especially to explore the effects of low-frequency vibrotactile stimuli on time perception, considering that 6 Hz is the lowest frequency evaluated by now, according to the recent literature. Tactile stimuli between 0 and 6 Hz, despite being sinusoidal oscillations, are perceived as independent successive and discrete events rather than as vibrations. That property can influence time perception due to its role as a compass that divides a long-time interval into smaller, regular and easier-to-estimate sub-intervals, a process similar to counting (Getty 1976). The present study intended to embrace those gaps exploring whether there are differences in perceived duration measured using a time reproduction task, performed by subjects stimulated with: first, several vibrotactile frequencies below 6 Hz; second, under different conditions (presence and absence of stimulus during reproduction); and third, using both paradigms of study (prospective and retrospective). In order to achieve that, two experiments were designed: one with bilateral, same frequency stimulation (Experiment 1) and another with bilateral, different frequency stimulation (Experiment 2). As an increase in the frequency of vibration stands for a higher number of events, it is expected that reproduced times increase thereupon and, hence, reproduced times should be different among frequency groups. Also, time distortions are expected to be lower for the tasks where participants performed the reproduction in the presence of the to-be-timed stimulus.

Experiment 1

Participants in this experiment performed three estimations using a time reproduction task, one retrospective and two prospective ones.

Participants

Participants (33 males and 67 females, mean age of 24 ± 6.5 years) were students and staff of the Faculty of Philosophy, Sciences and Letters of Ribeirão Preto, at University of São Paulo (FFCLRP) and did not report any motor or tactile perception problems. All participants were aware of the procedures but naive to the purpose of the experiment; they participated voluntarily and signed a written informed consent about the procedure. All procedures were conducted in accordance with and approved by the local ethical committee.

Apparatus

The vibrotactile stimuli were applied using two vibratory platforms of adjustable frequency, developed specifically for this experiment. The upper side of each platform was a square rubber surface of 900 cm^3 oscillating unevenly around an axis in the proximate side of the square, allowing participant's hands to have a greater amplitude of oscillation on the fingertip area rather than on the base area (see Fig. 1a). Platforms were placed over two individual tables

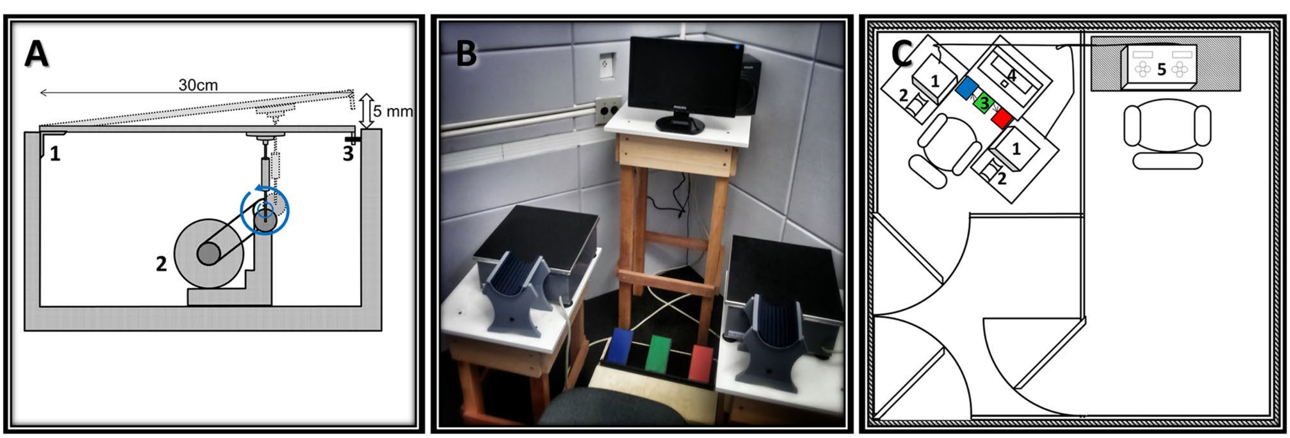

Fig. 1 Equipment: **a** simplified scheme of the vibratory platforms (1. Hinge; 2. Motor; 3. Optical frequency reader). **b** Experiment room. **c** Distribution of equipment and controls (1. Vibratory platforms; 2. Armrests; 3. Pedals to perform reproduction tasks; 4. Screen; 5. Platform control)

to avoid distortion or attenuation of the stimuli. Instructions were presented on a 15.6-inch-high definition monitor (60 Hz), using the WavSurfer v.2008 software, which was also used by participants to perform the time reproduction tasks (as displayed in Fig. 1b). This software was installed on an Acer E1-571-BR800 laptop with an Intel Core i3 processor of 1.7 GHz and 4.9 MB RAM. Time reproduction task was performed using a modified keyboard as a set of three pedals to, from left to right, start the experiment, initiate and stop time reproduction, respectively (Fig. 1b). Participants were inside an isolated, soundproof, experimental room (178 cm × 173 cm); tubular led white lights where they rested seated, with their elbows on supports, hands over the vibratory platforms (like Watanabe et al. 2010), feet resting on the blank space of the set of three pedals on the floor and an inactive computer screen in front of them. The equipment was controlled by the experimenter from a contiguous room as displayed in Fig. 1c.

Procedure

Retrospective task. Participants performed a time reproduction task and the experiment consisted of two main phases, a stimulation phase and a time reproduction phase. Participants were distributed randomly into five groups of stimulation defined by vibration frequencies (G0.5 Hz; G1.0 Hz; G1.5 Hz; G3.0 Hz; G6.0 Hz; $n = 20$ each group). Each group was also divided into two conditions: Stimulus Present during reproduction task (SP, $n = 10$) and Stimulus Absent during reproduction task (SA, $n = 10$).

Participants performed, individually, a time reproduction task. After a brief introduction in which the stimulus was described, but not the specific task to be performed, the participant was left alone in the room and after a few seconds, the stimulation phase began: both platforms were activated at the corresponding frequency (0.5–6 Hz depending on the participant's group). Stimulus duration was 8 s for every participant. When vibration was over, instructions about the time reproduction task appeared on the screen asking the participant to use the pedals to reproduce the stimulus duration: a blue pedal to start the time reproduction phase, a green pedal to start a stopwatch hidden from the participant, and a red pedal to stop counting; pedals should be pressed in that respective order. If the participant was in an SP group, platforms were activated in the time reproduction phase as soon as the participant pressed the green pedal, delivering the same frequency of the Stimulation phase, and shut down with the action of the red pedal; otherwise, platforms stayed still while the participant performed the reproduction. If the participant took more than two times the stimulus duration to press the red pedal, the experiment was finalised by the experimenter.

At the end of this task, participants answered the "Post-experiment Questionnaire" with questions about their experience during the task, including two Likert scales from one to seven asking about how complex (1: the simplest, and 7: the most complex) or uncomfortable (1: not at all, and 7: very uncomfortable) the stimulus was perceived.

Prospective task. Shortly after filling the questionnaire, participants were asked to perform two more estimations: stimulus and condition were assigned using a randomised list of the stimuli and conditions, for each participant. As at this time, participants were aware of the task they performed, the experimenter asked them to pay attention to time (prospective paradigm). At the end of the task, another "Post-experiment Questionnaire" was filled by participants.

Statistical analysis

Normality and homoscedasticity were assessed using Shapiro–Wilk and Levene tests correspondingly, to decide if differences among groups would be evaluated using parametric or non-parametric tests. As each experiment is a 5 × 2 design the 2-way ANOVA or Friedman tests were considered. After the formal statistical analysis, several post hoc tests were performed to expand the understanding of the results: *T* student tests for pairwise comparisons and non-linear regressions to explore data behaviour.

Results

Reproduced times (RTs) were normalised (NRTs), being zero when subjects matched stimulus duration. This kind of normalisation made it possible to easily identify longer or shorter reproductions. Data from participants who explicitly declared that they did not understand the task or that their estimation was longer than the double of stimulus duration were excluded (following Khoshnoodie et al. 2008). However, after the application of this criterion 95% of the reproduced times were under 12.65 s with a maximum of 15.52 s.

Retrospective task. The distribution of estimations performed among experimental groups is shown in Table 1. Homoscedasticity was tested and confirmed for all groups using the Levene test (Frequency $p = .384$ $df = 87$; Condition $p = .880$ $df = 90$). Shapiro–Wilk test was used to assess normal distribution and it was confirmed to all frequency groups and to SA condition (G0.5 $p = .67$ $df = 17$, G1.0 $p = .143$ $\mathrm{df} = 20$, G1.5 $p = .695$ $df = 17$, G3.0 $p = .106$ $df = 19$, G6.0 $p = .166$ $df = 19$; SA $p = .632$ $df = 47$).

A two-way ANOVA for RTs and NRTs, with Frequency and Condition as factors (5 × 2), did not show any differences between frequencies and conditions when reproduction task was performed in a retrospective paradigm. However, on the graphs, there seems to appear an opposite trend between

Table 1 Distribution of estimations among groups for the retrospective task

Experiment 1. Prospective task			
Stimulus	Condition	*n* (Cond.)	*n* (Freq.)
0.5 Hz	SP	8	17
	SA	9	
1.0 Hz	SP	10	20
	SA	10	
1.5 Hz	SP	8	17
	SA	9	
3.0 Hz	SP	9	19
	SA	10	
6.0 Hz	SP	10	19
	SA	9	
N			92

SP stimulus present, *SA* stimulus absent; *n (Cond.)* number of estimations per condition, *n (Freq.)* number of estimations per group of frequency

Table 2 Distribution of trials among experimental groups for E1b

Experiment 1.b			
Stimulus	Condition	*n* (Cond.)	*n* (Freq.)
0.5 Hz	SP	19	39
	SA	20	
1.0 Hz	SP	20	39
	SA	19	
1.5 Hz	SP	20	38
	SA	18	
3.0 Hz	SP	18	37
	SA	19	
6.0 Hz	SP	20	40
	SA	20	
N			193

SP stimulus present, *SA* stimulus absent, *n (Cond.)* number of estimations per condition, *n (Freq.)* number of estimations per group of frequency

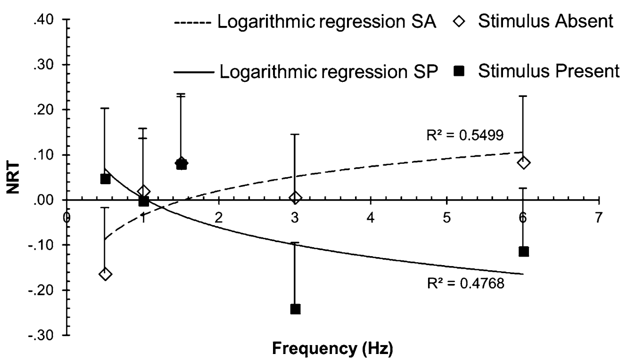

Fig. 2 Experiment 1. Retrospective task. Means of normalised reproduced times (NRT) separated by frequencies and condition (stimulus present or absent). Bars represent standard error of the mean (SEM). Two logarithmic regressions were performed to test data fitting

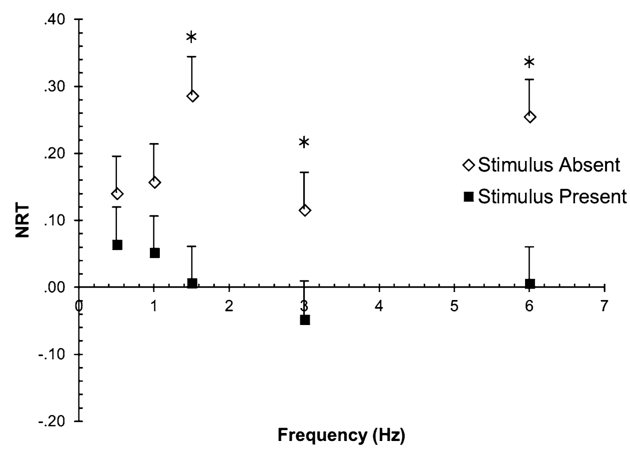

Fig. 3 Prospective task. Means of Normalised Reproduced Times (NRT) separated by frequency and condition. Bars represent standard error of the mean (SEM). *$p \leq .05$ on *t* student's test

conditions (Fig. 2). Data showed a mild fit to a logarithmic model, with opposite coefficients for each condition (SA: $B = 0.078$, $R^2 = 0.549$, sig. = 0.152; SP: $B = -0.094$, $R^2 = 0.476$, sig. = 0.197).

Prospective task. The same participants performed two more estimations under prospective paradigm. Table 2 shows the distribution of estimations among experimental groups. Homoscedasticity was tested and confirmed for all groups using the Levene test ($p = .447$, $df = 183$).

A two-way ANOVA, with Frequency and Condition as factors (5 × 2), did not show any differences in RTs between frequencies, but between conditions, RTs were longer in participants who performed the time reproduction task in the absence of the stimulus: $F_{(1,\ 193)} = 25.127$, $p < .01$, $\eta_p^2 = 0.128$.

Even though the statistical test did not show a significant difference among frequency groups, data suggest that differences between conditions become larger as stimulus frequency rises (Fig. 3). A student's *t* test was performed to assess SP versus SA condition for each frequency group finding significant differences for frequencies above 1.5 Hz (F3: $t_{(53)} = 2.024$ $p = .048$ Cohen's $D = 0.54$; F4: $t_{(54)} = 2.140$ $p = .037$ Cohen's $D = 0.58$; F5: $t_{(57)} = 2.654$ $p = .010$ Cohen's $D = 0.69$).

To verify whether differences between conditions increased as a function of stimulus frequency, the absolute value of the differences of RTs between conditions was calculated within each frequency group as follows:

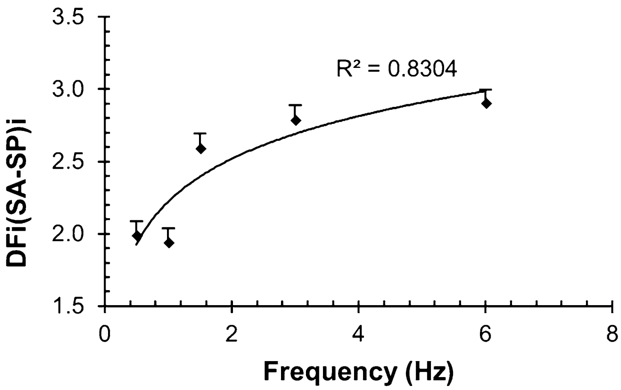

Fig. 4 Mean of the differences between SP and SA conditions (DF_i) as a function of stimulus frequency. Bars represent standard error of the mean. The line represents a logarithmic regression

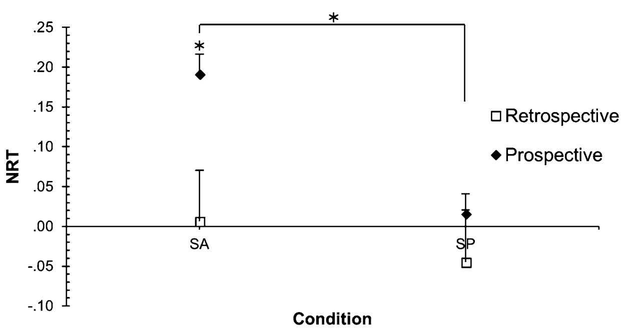

Fig. 5 Means of NRT for SA (stimulus absent) and SP (stimulus present) conditions between retrospective and prospective tasks. Bars represent standard error of the mean. *Significant differences assessed with paired student's *t* test ($p \leq .05$)

$$DF_{i(\mathrm{SA-SP})} = \frac{n\left(\mathrm{RT}_{\mathrm{SA}_i}\right) - \sum_{i=1}^{n}\left(\mathrm{RT}_{\mathrm{SP}_i}\right)}{n},$$

where $DF_{i(\mathrm{SA-SP})i}$ is the mean difference between each RT in the SA and each RT in the SP for each group of frequency. Hence, n values of mean differences were calculated for each group of frequency, being n the number of estimations performed under that frequency. A Kruskal–Wallis test showed that the distribution of the differences between the conditions among frequencies varied ($p=.000$; Fig. 4). Data significantly fitted to a logarithmic regression model ($B=0.426$, $R^2=0.8304$, sig. = 0.031).

Conversely, student's *t* tests were used to assess whether there were differences in NRTs between the retrospective and prospective segments of the experiment, for each condition (SA and SP). When stimulus was absent, NRTs were longer under the prospective paradigm rather than under the retrospective one [$t_{(64.34)}=-2.736$, $p=.008$ Cohen's $D=0.52$]. Differences were not found between paradigms when the stimulus was present during the time reproduction task (Fig. 5).

An analysis including the Likert scales about complexity and discomfort of the surveys showed a weak correlation between Discomfort scale scores and stimulus frequency. This correlation was assessed using Spearman test ($r=.18$; bilateral significance = 0.003). A Spearman test was also conducted between Complexity and Discomfort scores and NRT revealing a weak correlation between reproduced times and Discomfort score ($r=.13$; bilateral sig. = 0.021), but not between reproduced times and the stimulus Complexity score. However, the correlation between Discomfort and Complexity scores was the strongest one ($r=.376$; bilateral sig. < 0.001).

Experiment 2

Participants

Participants (41 females and 23 males) were students and staff of the FFCLRP and did not report any motor or tactile perception problems. All participants were naive to the purpose of the experiment, they participated voluntarily and signed a written informed consent about the procedure.

Apparatus

The same equipment as in Experiment 1 was used.

Procedure

Experiment 2 consisted of a single time reproduction task in a retrospective paradigm. For this experiment, two factors were controlled: base frequency (bF) and quotient of frequencies (Q). Since the aim of the experiment was to assess the effect of contextual frequencies, two basal frequencies (bF1 = 2 Hz, bF2 = 12 Hz) were established and four comparison frequencies (cF) were determined using two values of Q ($Q1=0.5\times bF$, $Q2=0.75\times bF$). Task stimulation outline is summarised in Table 3. Participants were assigned to one of the possible outlined tasks using a randomised list of tasks.

Participants were guided individually into a quiet room in which they rested as in Experiment 1 using a retrospective paradigm. Stimulation consisted of two vibrations with different frequencies: base frequency (bF), lasting for 13 s, and the comparative frequency (cF), lasting 8 s. Comparative frequency started 5 s after base frequency so participants had 8 s of simultaneous stimulation. Base frequency was counterbalanced between right and left hand among participants using blocks (see Table 3).

Table 3 Experimental design and distribution of the estimations for Experiment 2

Quotient of frequency ($Q_i = cF/bF$)	Base frequency (bF)	Block	*n* (block)
0.5	2 Hz	R	9
	2 Hz	L	6
	12 Hz	R	7
	12 Hz	L	7
0.75	2 Hz	R	9
	2 Hz	L	7
	12 Hz	R	9
	12 Hz	L	10
N			64
Tempo	8 s		

Results for 80 participants without excluded cases using the same criteria as in Experiment 1. Factor 1 divided participants into two groups per frequency quotient (Qi) between base frequency (bF) and comparative frequency (cF). Factor 2 establishes the value of base frequency. Blocks account for the hand to which base frequency was delivered (R: Right; L: Left), *n* (block) represents the number of estimations per block on each Qi and bF

When vibration was over, instructions about the time reproduction task appeared on the screen asking the participant to use the pedals to reproduce the duration of simultaneous stimulation (8 s) as in Experiment 1. In this case, all participants performed the time reproduction task in the absence of the corresponding stimulus. At the end of the experiment, participants answered the same "Post-experiment Questionnaire" used in Experiment 1.

Results

Data from 64 participants were considered (41 females and 23 males) and distributed as shown in Table 3. When analysing NRTs, neither they nor their transformations showed normal distribution or homoscedasticity; hence, nonparametric tests were conducted.

Mann–Whitney's *U* test showed significant differences between fps but not between quotients (bF: $p = .034$; Q: $p = .415$). Figure 6 shows the means of NRT for each quotient (A) and for the total mean for each group of bF (B). Spearman tests were conducted and showed a mild-to-weak correlation between base frequency and NRT ($R = -0.267$; Bilateral sig. = 0.033) but no correlation at all for frequency quotient.

Discussion

First, this study intended to broaden the knowledge in the field of subjective time perception when that process was under the effects of vibrotactile stimulation. Therefore, two experiments were planned with a range of frequencies not yet assessed in the present literature. Those frequencies were of great interest because of the presumable effects they could have at the time scale used (long intervals of 8 s.

The first goal intended to assess subjective time perception as a function of a vibrotactile stimulus frequency; consequently, in both experiments, participants had to reproduce the duration of different kinds of vibrotactile stimuli. In Experiment 1, no differences were found for NRTs

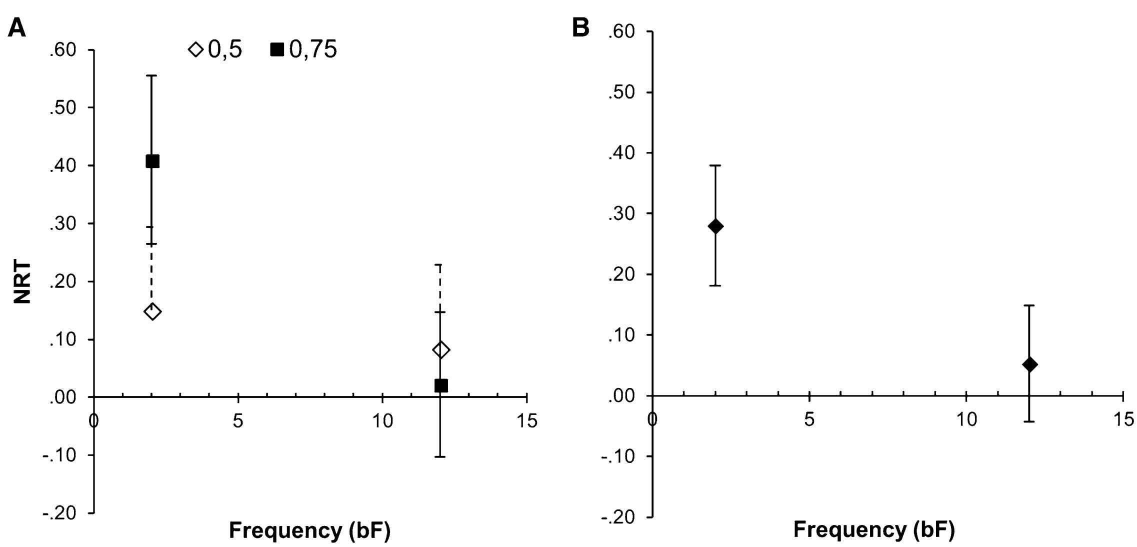

Fig. 6 Means of NRT (normalised reproduced times) as a function of base frequency (bF) for Experiment 2, separated by quotients (**a**) and as an entire sample (**b**). Bars represent standard error of the mean

among frequencies (between 0.5 and 6 Hz) using a two-way ANOVA, but it was found a weak tendency, opposed to what is seen in some literature (for instance, Khoshnoodie et al. 2008) at least when using the regular procedure (in the absence of the stimulus during reproduction) and RTs were longer while frequency increased. It is worth noting, however, that this behaviour was also reported for tactile stimuli by Tomassini et al. (2011) when they increased the speed of a corrugated grating on a wheel touched by participants. In that case, vibrotactile frequency is proportional to the speed of the wheel.

Nevertheless, means of NRT in Experiment 2, which have a wider range of frequencies than Experiment 1 (from 1 to 12 Hz), were significantly different among groups of base frequency; the value of the effect sizes of the tests was in the range of a medium size effect, which gives confidence to our results. Therefore, it is probable that the lack of variation found in E1 was due to the narrow spectrum of frequencies used in this study and absent in the consulted literature (Khoshnoodie et al. 2008). However, it is worth to note that these findings are not proof of the absence of differences since Bayes factor was not estimated. Considering data collected in Experiment 2, it is possible to find an inverse correlation between NRT and frequency. It is indeed quite impressive because, with this broader range of frequencies, estimations began to match literature with outstanding precision. For example, the intersection with x-axes (when reproduced time equals stimulus time) in Khoshnoodie et al. (2008) experiments happened when frequency of test stimuli was around 12 Hz, almost the same as in the present study (see Fig. 5), thus corroborating previous studies with tactile stimuli (Khoshnoodi et al. 2008; Tomassini et al. 2011) but also studies in different sensory modalities (Matthews 2013; Nather et al. 2011, 2013; Nather and Bueno 2011).

The trend of RTs as a function of frequency is totally opposed between the conditions of the presence and absence of the stimulus during the reproduction. Hence, although some of our results are opposed to what is typically found in the literature, as stated above, this applies precisely to the new conditions tested here. The second goal here was to test whether there are any differences in subjective time when the stimulus is present or absent during the time reproduction task. The closest task to this comparison may be the analysis of estimation of peri-gap time designed by Khoshnoodi et al. (2008) where, though they did not report significant differences between peri-gap frequencies, the slope of RTs among frequencies was also opposed between filled and empty gaps. Since Experiment 1 showed a clear change for the conditions of the absence or presence of the stimulus, this could suggest that what is distorting time perception is the presence of stimulation during the reproduction rather than the characteristics of the stimulus, contrary to what was found in previous studies (Khoshnoodi et al. 2008; Tomassini et al. 2011).

In Experiment 1, the SP or SA condition, during the reproduction, only showed differences in NRTs for the prospective paradigm, where participants performed longer estimations while the stimulus was absent. This is in agreement with Block and Gruber (2014) since the results highlighted the role of attention to the temporal properties of a stimulus in the distortion of time perception.

The differences in reproduced times could be interpreted as follows: in the stimulation phase, the counting compass is synchronised to the vibratory stimulus, not necessarily in a one-to-one proportion, but depending on the oscillation frequency, dividing total duration into regular subintervals. Hence, the number of subintervals would increase as frequency increases. In the reproduction phase, while the stimulus was present, the counting compass remained the same, but when the stimulus was absent and counting compass returned to a basal state, it took more time to reproduce the same number of subintervals in which total duration was discomposed. This is an analogous process to the one described by Getty (1976), where counting attenuates the distortions in time estimation because a big lapse is divided into smaller and easier-to-estimate ones and, according to Weber's law, smaller errors too.

Estimated times increase in a linear way as a function of the to-be-timed duration and of the speed of the pacemaker (Mattheus and Meck 2016). However, there is no mathematical consensus on the relation between non-temporal properties of stimuli and estimated times. For example, Ekman et al. (1969) showed that estimated times kept a logarithmic relation with the intensity of vibrotactile stimuli, but others have shown different functions (Block et al. 2010; Firmino and Bueno 2008; Khoshnoodi et al. 2008). If analysing under the internal clock model, variations in reproduced times on this study could only be due to the acceleration of the pacemaker, because stimulus duration was always the same. Nonetheless, other models based on network activation (Karmarkar and Buonomano 2007) or amount and complexity of information being processed (Ornstein 1969) would fit as well to the data collected in this study.

The present study, as well as the ones in the literature up to this time, acknowledges frequency or speed as the variable inducing time distortion, but there has been a lack of modulation of the energy released by the stimulus in the experiments using vibrotactile stimulation. The responses of tactile receptors are different against pressure or against the frequency of stimulation, but this difference is not shown by the amplitude of action potential, as demonstrated by Bolanowsky and Zwislocki (1984a, b) in Pacinian corpuscles. The difference is reflected in the frequency and threshold of response of the receptor. As frequency increases, if the amplitude of the oscillation remains constant, the speed of the oscillating surface also increases and, for definition, the kinetic energy and the pressure released to the surface in contact (the skin). Hence, observed distortions could be due to variations in the stimulus frequency or due to variations in the pressure against the skin. No study consulted during the development of this research claims to assess the effects of amplitude modulation, considers it as an issue, or even mentions it. Designing experimental procedures that apply a modulation in the amplitude as a function of the frequency would broaden the conceptual and experimental scope and assist in the identification of the variables responsible for distortions in subjective time.

Several issues in the study of time perception remain unclear: the functional value of a flexible subjective time, the suitability of a model of time perception based on a dedicated timing device so susceptible to external factors, the diversity of perceptual processes and the integration of perception and cognition (Mattheus and Meck 2016). Addressing the value of a flexible subjective time, one can ask if there is any advantage that can be taken from lengthening or shortening an individual's time perception, for example regarding memory and attention performance. In order to do so, adequate experimental protocols are needed but the relations between cognitive processes with time perception make it harder. Even more, considering that asking a subject to perform simultaneous cognitive tasks can bias results, especially if the tasks involve the use of a unique sensory modality (Auvray et al. 2008). As many studies have exposed, there are significant effects of sensory integration and crossmodal perception over cognitive processes (for example: Brunetti et al. 2017; Chen and Zhou 2014; Hopkins et al. 2017; Noesselt et al. 2007).

Traditionally, researchers have studied the effects of cognitive tasks over time perception (i.e. Block et al. 2010), but not the other way around. This is mainly because subjective time is understood as an integral part of the experience of an event (Block 2003) and, consequently, a cognitive task becomes part of what defines the temporal experience of the lapse where it occurs. However, data obtained in the present study, regarding variations in subjective time perception as a function of absence or presence of the stimulus in the reproduction phase, establish a benchmark to design new protocols. This is due to the fact that the time distortion appeared while recalling the duration in the absence of the stimulus. Putting this together with the results obtained by Khoshnoodie et al. (2008), where perceived duration depended on the proportion of the frequencies during stimulation and reproduction phase, we suggest that the change in the sensory context is, at least in part, responsible for the distortion. Hence, a second cognitive task can be asked taking care to not interfere in that contextual change. Investigating the crossmodal interactions in this kind of procedure may open the possibility to determine the tasks and sensory modalities which allow to asses if there are differences in some cognitive functions while a participant is experiencing a distortion of time.

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