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A novel Android app to evaluate and enhance auditory and tactile temporal thresholds*

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Abstract— **With this work, we introduce a novel Android app designed to monitor and enhance auditory and tactile temporal sensitivity. To assess the app's reliability, we tested its technical performance evaluating stimuli production's accuracy (i.e., onset, offset, and duration of stimulation). To validate the app with participants we generated temporal intervals, using either sounds or vibratory stimuli, by implementing two versions of a Two-Alternative Forced-Choice (2AFC) task. Auditory and tactile temporal sensitivity of 12 participants was evaluated using this procedure. To investigate whether temporal abilities could be enhanced using the app, participants were then divided into two groups: one group was trained for four days on the auditory temporal task, while the other was trained for four days on the tactile temporal task. Results suggest that the app can i) effectively measure auditory and tactile temporal thresholds and ii) be used to enhance temporal abilities through perceptual learning. The accessibility of the experimental protocols, combined with our findings, fosters the app's involvement in rehabilitation programs, for example, with a specific focus on sensory disabilities that are associated with temporal deficits (e.g., deafness and Parkinson).**

Clinical Relevance— **The current work introduces a novel app that can be used to monitor and improve temporal abilities, in both the auditory and the tactile modalities.**

I. INTRODUCTION

How long is a second? In 1967, after the initial diffusion of atomic clocks, the duration of a second was defined as "the duration of 9,9192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the caesium-133 atom". With such accuracy, nowadays, time intervals have been mastered so that two satellites can be synchronized within the nanosecond range. Nonetheless, if we ask a person to show us how long a second is, for example, tapping on a table's surface, we will hardly obtain a temporally accurate response. Moreover, if the same person answers again, most certainly the response will differ from the previous one. It is not surprising that living systems lack the temporal precision of artificial clocks. Biological processes are essentially stochastic, and noise is one of their fundamental part [1]. Yet, it is startling to witness to what extent subjective time can be anisomorphic to physical time, considering that temporal patterns are crucial for many aspects of action and perception [2-3] and that our entire relationship with the environment is based on time-varying events. Humans are so sensitive to changes in temporal structures that evolved specific mechanisms to both tell time and learn to reproduce it [4-5]. Since the discrepancy between physical and subjective time is exacerbated in specific neurological and sensory disabilities [6], e.g., Parkinson's disease [7] and deafness [8], a growing body of research on enhancement of neural temporal dynamics has recently emerged to support clinical intervention. Whether we investigate temporal skills in research or a clinical setting, a handy estimation of temporal thresholds is an overall valuable tool. Even though the assessment of temporal abilities can be done in a timely fashion, it often requires expensive technical setups with above-average performance. Moreover, evaluation of temporal skills is strictly limited by the accessibility to the research/medical centers in which these setups are held. Undeniably, the recent COVID-19 outbreak strongly reduced such accessibility, making temporal evaluations (and other clinical/scientific evaluations) even more difficult to obtain. The pandemic's consequences notwithstanding, accessibility issues have always been prominent in at least two cases: first, when temporal evaluations must be conducted on patients that have mobility difficulties, e.g., when it is complex for a patient to reach the medical center due to distance and transportation; second, when the evaluation takes several days, and the drop-out risk must be considered, e.g., when implementing a temporal perceptual learning protocol. In this context, here, we challenge both issues by developing PsySuite (Psychophysics Suite). *PsySuite* is a novel, user-friendly Android app designed to deliver multimodal (acoustic, visual, and tactile) stimuli. We designed PsySuite combining the affordance of an everyday device with the rigorous methodology of psychophysics, a branch of neuroscience research that investigates the quantitative relations between psychological and physical events. Within the app, the temporal interval discrimination (*TID*) test was implemented. *TID* was designed to evaluate and enhance temporal skills in both auditory and tactile sensory modalities, through classical psychophysical methods as a Two-Alternative Forced-Choice (2AFC) tasks. We decided to develop a portable version of such task since it has been extensively used to assess temporal thresholds in the past [9]. The aim of this work is twofold. On the one hand, we wanted to validate the evaluation of auditory and tactile temporal

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thresholds using modern Android smartphones, which are affordable and easily handled. On the other hand, we wanted to prove that temporal perceptual learning's specificity can be achieved also using non-canonical rehabilitative and experimental setups. Our results support TID's feasibility in investigating and enhancing auditory and tactile temporal thresholds, suggesting that our app can potentially be a valuable tool for clinical assessment and rehabilitation protocol implementation.

II. METHODS

A. *Temporal Thresholds Reliability Assessment*

12 participants were recruited for this study (7F; *mean age*=28±1.21 years) after giving written consent in accordance with the local Ethics committee (ASL3 Genovese) and the declaration of Helsinki. To evaluate auditory and tactile temporal sensitivity, we implemented within *TID* two versions of the classic psychophysical 2AFC task (one for each sensory modality: hearing and touch). In a 2AFC task, two stimuli that differ in one or more perceptual features are sequentially presented. One of the stimuli, the *test*, changes in feature across trials, while the other, the *reference*, does not change during the whole procedure. Asking participants to discriminate which of the two stimuli lasts longer allows evaluating specific parameters that describe the perceptual performance. With this procedure, we can define the Just Noticeable Difference (JND), which identifies the perceptual threshold and is an index of precision, and the Weber Fraction (WF), which identifies perceptual sensitivity and is the ratio between the JND and the physical intensity of the stimulus. In the current study, we decided to describe temporal sensitivity using WF, since it is dimensionless and can be more easily compared with existing literature. In our tasks, participants had to discriminate between two sequentially presented durations, indicating which one lasted longer. Stimuli were empty intervals delimited either by 50-ms sounds (in the auditory 2AFC task) or phone vibrations (in the tactile 2AFC task), separated by an inter-stimulus-interval (ISI) of 500-ms (Figure 1). The *reference* interval was fixed at 200-ms in both tasks, while the *test* interval lasted one of eight pre-configured duration (100, 128, 157, 185, 214, 242, 271, and 300-ms). Each duration was randomly presented eight times within the same block so that a block consisted of 64 trials. All tasks were run adding a white noise background to mask the sounds produced by the vibrator engine and ensure participants relied only on tactile cues when available. Moreover, since white noise generation could have altered smartphones' general performance, we decided to add white noise background to the auditory 2AFC task. Thereby, we asked participants to wear headphones during each block's completion, regardless of the sensory modality involved.

B. *Temporal Perceptual Learning Assessment*

To assess whether temporal perceptual learning protocols can be implemented using *TID* within the Psychosuite app, we divided participants into two equinumerous groups (6 participants per group). One group (3F, *mean age*=27.75±0.5 years) was trained for four days with the 2AFC auditory task, while the other (4F, *mean age*=27.83±1.47 years) was trained for four days with the 2AFC tactile task. During the training, *TID* provided feedback at the end of each trial: if the participant succeeded in indicating the longer stimulus, a green checkmark appeared on the mobile display to notify the correctness of the answer; otherwise, if the participant failed to give the correct response, a red cross was displayed. We provided feedback only during training sessions since reinforcement from internal rewards increases learning rates [10]. During each training session, participants completed three blocks for a total of 192 trials. Training sessions took about 15 minutes to complete and were performed at home. The day after the training session ended, participants completed 2 more blocks of the corresponding trained task. WF measured after the training (*post-training thresholds*) were then compared with WF measured before the training (*pre-training thresholds*). In next paragraph, we will discuss all relevant technical aspects for both the app implementation and validation.

C. *App Implementation and Validation*

PsySuite was developed using Kotlin language, the AndroidX packages libraries, and was built for Android 10 version. Audio stimuli were delivered using a C++ native solution implemented through the Oboe library (https://github.com/google/oboe). This solution adopts the AAudio native library and allows high-performance audio apps by automatically tuning and optimizing audio latencies. To may playback low-latency audio streams, stimuli shall be sampled at the system optimum sampling frequency and encoded in an uncompressed format. We thus opted for storing our audio stimuli in an uncompressed 16-bit PCM format, sampled at 48KHz, and saved as WAV file. Such stimuli were preloaded in a dedicated audio buffer at the beginning of each test to be later repeatedly played with the smallest latency possible. At the end of each test, these audio resources were released. Tactile stimuli were delivered using the Android's VIBRATOR_SERVICE and then regulated by the vibrate and cancel methods of the Vibrator class. Experiments were run on a Xiaomi Mi A2 Lite smartphone bought in 2018, equipped with 3 GByte of RAM and a Qualcomm® Snapdragon ™ 625 Octa-Core processor running at 2.0 GHz using Android version 10. The accuracy and precision of the produced stimuli were measured through

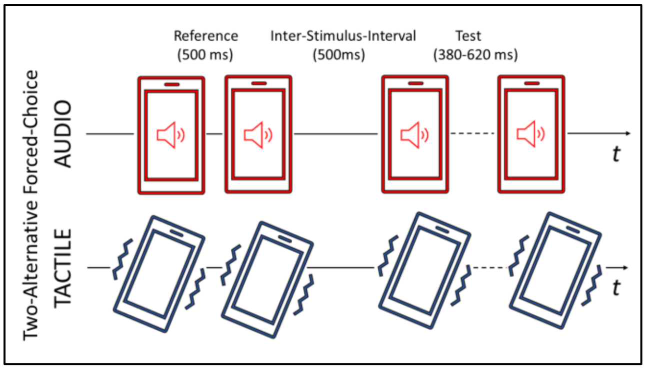

Figure 1. Schematic representation of both auditory and tactile procedures. At the end of the stimuli presentation, participants had to select which one lasted longer. Dashed lines between test onset and offset indicate that the Test's duration changed across trials.

a TDS 2014B Tektronix oscilloscope. Vibrations produced by the smartphone were measured through a brass, disk-shaped (diameter 27 mm, thickness 0.40 mm) piezoelectric sensor. Smartphone audio was collected from its 3.5” jack output. Each sensor was connected to a different channel of the oscilloscope through crocodile cables.

III. RESULTS AND DISCUSSION

A. Temporal Thresholds Reliability Assessment

We validated *TID* evaluating stimuli production’s accuracy (i.e., onset, offset, and duration of stimulations). Technical validation was carried out comparing oscilloscope’s traces of auditory and tactile stimuli with their supposed duration. Graphical inspection of oscilloscope’s traces confirmed that *TID* was able to maintain high accuracy when presenting temporally spaced stimuli (Figure 2). Consequently, the app accurately displayed not only all temporal intervals (intervals’ duration) but also both 50-ms stimulations delimiting the intervals (intervals’ onset and offset). Thereby, we concluded that *TID*’s stimuli presentation was sufficiently stable to allow reliable temporal threshold evaluation. Behavioral validation was carried out comparing temporal thresholds measured with *TID* against the ones reported in the existing literature ([11-12]), evaluated using only classic psychophysical methods. To assess the reliability of temporal thresholds measured with *TID*, we performed one-sample t-tests on WF assuming literature values as population means (Auditory WF=0.132; Tactile WF=0.154). Then, we compared WF across sensory modalities using a paired-samples t-test, since we expected WF in the auditory modality to be lower than WF in the haptic modality [13]. Statistical analyses highlighted two major findings: first, WFs obtained with *TID* did not differ from population WFs neither in the auditory (one-sample t-test: $t_{(11)}=1.308$, $p=0.22$; $d=0.378$) nor in the haptic (one-sample t-test: $t_{(11)}=1.93$, $p=0.08$; $d=0.55$) modality; second, WFs measured in the auditory modality were significantly lower than WFs measured in the haptic modality (paired sample t-test: $t_{(11)}=-2.882$, $p<0.05$; $d=-0.832$), as clearly reported in Figure 2. These trends are both in line with expected measurements obtained via classic psychophysical procedures. Taken together, these results strongly support *TID*’s feasibility in evaluating both haptic and auditory temporal thresholds, suggesting that our app is as reliable as the classical psychophysical method.

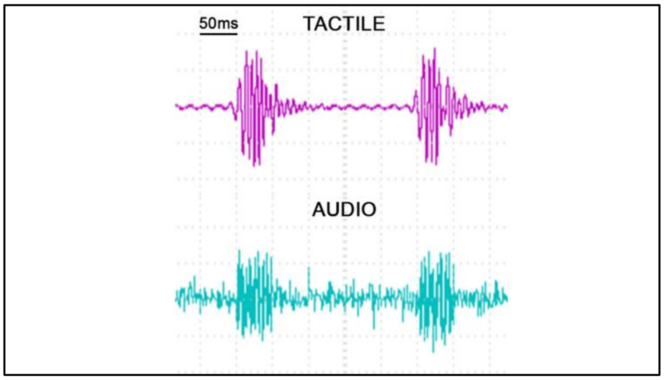

Figure 2. Produced stimuli. Example of tactile (upper, purple line) and auditory (lower, cyan line) oscilloscope’s traces of 200-ms temporal intervals, either delimited by 50-ms phone vibrations or sounds.

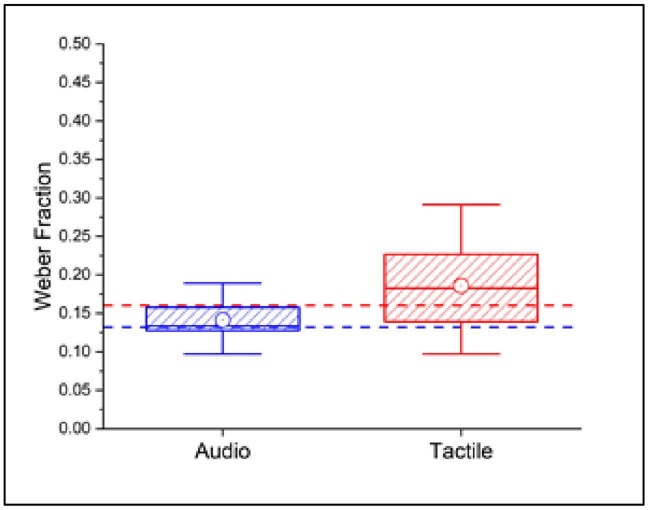

Figure 3. Estimated Weber Fractions using TID. Dashed lines indicate the population’s reference values for auditory (blue) and tactile (red) temporal perception. Within the boxplots, white circles indicate the mean, while continuous lines indicate the median of the distributions.

B. Temporal Perceptual Learning Assessment

If temporal perceptual learning can be induced using *TID*, we expect a reduction of WF due to the training’s benefit, regardless of the trained sensory modality. To evaluate sensory improvement for each participant, we compared *pre-training* and *post-training* WFs using statistical analysis. To achieve better statistical power and strengthen our results, we included in the same analysis both trainings simultaneously. Thus, we ran a 2x2 repeated measure ANOVA on WF with factors *modality* (acoustic vs. tactile) and *session* (pre-training vs. post-training). We found a main effect of *modality* ($F_{(1,10)}=24.825$, $p<0.001$, $\eta^2=0.54$) and *session* ($F_{(1,10)}=25.26$, $p<0.001$, $\eta^2=0.166$), but no significant interaction between factors ($F_{(1,10)}=0.393$, $p=0.545$, $\eta^2=0.003$). Given our statistical design, we did not need further comparisons. These results confirm that WF was generally higher in the tactile than in the auditory modality and that the training determined a reduction of WF for both groups (Figure 4A). To analyze training effects separately, we evaluated the difference in WF between the pre- and the post-training sessions, and then we compared the obtained values against zero. If training affected temporal sensitivity, we expect that the difference in WF before and after the training would be significantly different from zero. Thus, we performed one-sample t-test against zero for both sensory modalities. Our statistical analysis highlighted that the difference between the pre- and the post-training session was different from zero both in the auditory ($t_{(5)}=4.847$, $p<0.01$; $d=2.02$) and in the tactile ($t_{(5)}=2.68$, $p<0.05$; $d=1.094$) sensory modality. Since difference values were positive numbers, these results confirm that temporal sensitivity was lower in the *post-training* than in the *pre-training* session, both when temporal intervals were delimited by sounds or by phone vibrations (Figure 4B). In light of these results, we conclude that our protocol was overall effective in enhancing temporal skills as WFs were significantly lower in

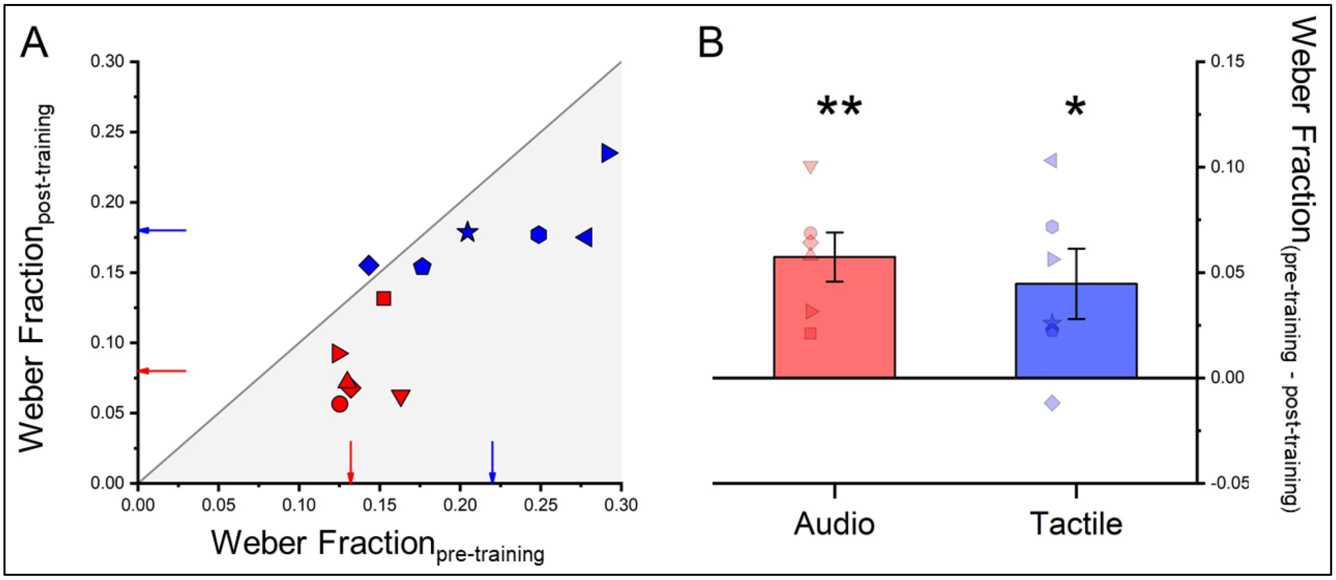

Figure 4. A) Post-training WFs plotted against pre-training WFs. Each point identifies a single participant. Red points represent WFs measured in the audio 2AFC task, while blue point represent WFs measured in the tactile 2AFC task. If a point is located within the grey area, the participant improved in the post-training session. This figure confirms statistical results reported in the main text, as it is evident not only how participants generally improved after the training, but also that measured WFs were lower in the auditory than in the tactile temporal task. Arrows near graph's axis indicate group averages. B) WFs differences between pre- and post-training sessions. For both groups, the training performed using TID determined a significant reduction of WFs in the post-training sessions. Scattered points indicated single participants, while error bars indicate ±SEM. (=p<0.05, **=p<0.01).*

the *post-training* sessions. These findings suggest that trained participants improved their performance after four days of home training, in an unsupervised environment, and through a simple and affordable device such as a smartphone.

IV. CONCLUSIONS

We presented *TID*, a test included within the novel Android app PsySuite designed to assess and enhance temporal perception skills in both auditory and tactile sensory modalities. Our results support the app's stability and reliability and confirmed that evaluating temporal skills does not necessarily require participants to reach research centers and hospitals, but can be remotely and safely done using an everyday tool such as a smartphone. Furthermore, we demonstrated that temporal perceptual learning could be conveyed using inexpensive and affordable setups, like the one that we propose with the current work. These results combined suggest that *TID* will evaluate temporal abilities easier for both researchers and medical staff. Notably, temporal impairments are often associated with different clinical conditions, such as Parkinson's disease and deafness. Thus, preemptive screening and intervention are crucial to investigate the neural substrates affected by the clinical condition itself and counteract the deterioration of the patient's quality of life. We are confident that *TID* will be a valuable addition in both scenarios since it was specifically designed to be user-friendly, affordable, and easy to distribute, to equally be suitable in research, clinical, and rehabilitation settings.

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