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A novel multisensory device for the assessment and rehabilitation of perceptual and attentional competencies*

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Abstract—**The present study aims to assess a novel technological device suitable for investigating perceptual and attentional competencies in people with or without sensory impairment. The TechPAD is a cabled system including embedded sensors and actuators to enable visual, auditory, and tactile interactions and a capacitive surface receiving inputs from the user. The system is conceived to create multisensory environments, using multiple units controlled separately and simultaneously. We assessed the device by adapting a spatial attention task comparing performances in different cognitive load conditions (high or low) and stimulation (unimodal, bimodal, or trimodal). 28 sighted adults were asked to monitor both the central and peripheral parts of the device and to tap a target stimulus (either visual, auditory, haptic, or multimodal) as fast as they could. Our results suggest that this new device can provide congruent and incongruent multimodal stimuli and quantitatively measure parameters such as reaction time and accuracy, allowing to investigate perceptual mechanisms in multisensory environments.**

Clinical Relevance—**The TechPad is a reliable tool for the assessment of spatial attention during interactive tasks. its application in clinical trials will pave the way to its role in multisensory rehabilitation.**

I. INTRODUCTION

Perception is enhanced and more precise when different sensory modalities are combined through multisensory integration [1, 2]. Nevertheless, the effectiveness of multimodal stimuli in detection tasks is affected by conditions such as perceptual and cognitive load [2, 3], or by the type of task [4]. Moreover, only some senses have the same weight: vision is the predominant sensory modality for many tasks, especially spatial ones (e.g., localization) [5], being capable of biasing the other modalities (i.e., hearing and touch) [6]. Furthermore, several clinical studies have shown that the absence of visual experience could negatively affect different areas of development, including spatial cognition [7]. Specifically, many spatial abilities (e.g., orientation and localization) arising early in childhood are deeply related to the visual experience [8]. As a consequence, early and multisensory (re)habilitation has been recommended for visually impaired (VI) children [9]. Recent studies have suggested that competencies such as perception and encoding of environmental events may benefit from multisensory activities [10, 9, 11].

Over the last few decades, there has been a growing interest in the effect of visual deprivation on development and in the design of technologies to support VI people. For example, multisensory devices have been validated and successfully used to investigate spatial competencies in sighted and blind adults [5, 12]. Nevertheless, many of the existing solutions have yet to be accepted by adults and need to be more adaptable to activities with children [13]. To date researchers have mainly focused on the design of assistive devices, while (re)habilitation solutions based on multisensory integration have been scarcely explored, especially in children (see, for example [14, 15]).

To fill this gap, we present a new technological system (the TechPAD) that could be used both for quantitative assessment and for (re)habilitation of perceptual and spatial competencies in people (both adults and children) with sensory impairment relying on both unisensory and multisensory mechanisms.

II. METHODS AND MATERIALS

To assess the system, as in [16], a group of sighted adults had to perform a spatial attention task derived from Lunn et al. [3]. Thanks to its sensors and actuators, the TechPAD can deliver visual, auditory, and vibrotactile stimuli, and directly record subject's responses. Furthermore, it has a tablet design that can be rotated in space. The touch surface allows participants to interact with various kinds of stimuli (any color and sound, including semantic ones). These characteristics make the TechPAD a suitable device for attention and tracking tasks based on unimodal (i.e., visual, auditory, and tactile) and multimodal stimuli. It may be suitable for tabletop activities in people of different ages, with different visual profiles, regardless neurological impairment.

A. *TechPAD – Mechanical Design*

The device comprises 12 identical tiles each of which is equipped with 64 touch sensors, eight LEDs, four vibromotors, and four speakers. The tiles are integrated with an external support structure that can be tilted with apposite knobs placed on the sides. The mechanical design was conducted with the PTC Creo Parametric 7.0 3D CAD platform. The setup was designed to simplify its construction as well as subsequent changes and design iterations. It thus comprises almost exclusively parts made in additive manufacturing (AM, also known as 3D printing), except for two steel plates that grant it structural stability. AM is advantageous in the

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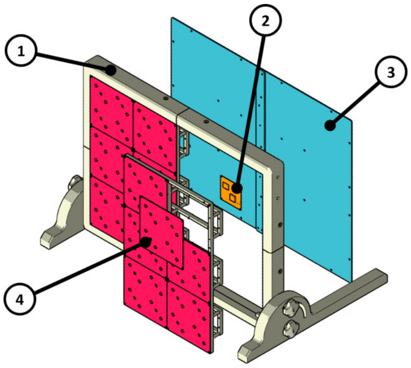

Fig. 1. CAD exploded view of the TechPAD and its main components: outer support frame (1), module command board (2), steel support plates (3) and sensing/actuators module (4).

development of such devices as it allows savings in cost and development time, facilitating design iterations. The plastic parts were fabricated in black ABS on a Stratasys Fortus 400 mc fused filament fabrication machine. Steel plates are of simple geometry and can be fabricated in any workshop equipped for sheet-metal fabrication. The final design is represented in Fig. 1.

B. TechPAD – Electronics and Firmware Design

The system contains 12 equal tiles, each comprising the following actuators and sensors: i) four banks of 16 touch sensors interfaced with an Infineon CY8CMBR2016-24LQXI capacitive read-out circuit, ii) eight RGB LED (with high luminosity to generate diverse visual stimulations distributed in the tile), iii) four vibromotors with relative driver (Precision Microdrives with eccentric shape controlled by a MAX1749 to guarantee a stable supply to the motor), iv) four digital class D amplifiers that drive four relative mini speakers (25 mm diameter). Each tile comprises also an ATMega328P microcontroller, used at a reduced clock speed of 8 MHz to maintain low-power consumption. It is in charge of interfacing all these sensors and actuators using both SPI and I2C interface buses. The electronic block scheme is shown in Fig. 2. Each tile is implemented in a single 106 mm × 106 mm × 1.4 mm Printed Circuit Board (PCB) module. An RS485 interface bus (InterFace/Sound Module, IF/SM) connected through a flat cable connects each tile with the others and with a device capable of generating sounds to be played by each tile's amplifier. The IF/SM is implemented in a 50 mm × 50 mm × 1.4 mm PCB. The module also comprises an SGTL5000 Audio Shield for Teensy, a board capable of outputting sounds from an external 4 GiB µSD card where custom sounds can be memorized in a 44.1 kHz PCM format and remotely played. Each of the 12 tiles has a unique address, allowing a maximum of 255 tiles. TechPAD also comprises an external remote controller (Fig. 2, bottom left) interfacing with the RS485 interconnection bus. The remote controller is based on an FTDI transceiver. It receives commands from the Personal Computer (PC) through a USB-emulated Virtual COM port and converts them into the RS485 protocol. An external medical grade power supply (5 V, 4 A) powers the complete electronics sub-systems. The current firmware supports the asynchronous read of the touch sensors and the asynchronous activation of all the transducers for each tile. The high-level management software, implemented on the PC, can then asynchronously address overall 768 touch sensors, 96 RGB LED, 48 speakers and 48 haptic motors. The device was controlled by a Python3 program run on a GNU/Linux machine (Dell Latitude 5420, Memory 16 Gib, Processor 11th Gen Intel® Core™ i5-1145G7 × 8), connected via USB. The program presented the stimuli according to the design setup, as described in Section II-C.

C. Experimental Protocol

We adapted a previous experimental protocol [3] (Fig. 3). 28 sighted adults (23 F, 5 M; age M=28.5 years old, SD=2.7 years) were enrolled from among residents working at IRCCS Mondino Foundation, Pavia, Italy. The protocol was approved by the local Ethics Committee (Fondazione IRCCS Policlinico San Matteo, Pavia, Italy) and all participants gave their written informed consent. Participants were provided written instructions. The experiment consisted of a central task and a concomitant peripheral task. Participants were required to monitor the center of the TechPAD, where a stream of target and not-target (distractors) visual stimuli (duration: 367 ms, separated by an off-period of 233 ms) was presented. As in the original paradigm, the central target (CT) could be presented either in a low-load condition (LLC) or a high-load condition (HLC). Distinction between target and distractor stimuli was based on the color in the LLC (4 red vs. 4 blue LEDs) and on the number in the HLC (4 red vs. 3 red, to allow subitizing – see [17]). Red and blue were chosen since they are easily recognizable primary colors at opposite parts of the wavelength spectrum.

In the peripheral task, participants had to monitor the left and right parts of the device, where the peripheral target (PT) could appear. Participants were required to tap on both the CT and the PT as accurately and quickly as possible. Differently from the CT, the PT could either be unimodal or multimodal. Unimodal stimuli were either 4 white LEDs (visual modality, V, duration: 100 ms), a sound (auditory modality, A, duration: 100 ms, 1100 Hz pure sine wave), or a vibration (haptic modality, H, duration: 250 ms). Multimodal stimuli could be a combination of two (i.e., HA, VA, VH) or three modalities (i.e., AVH). Peripheral stimuli could randomly appear during the central task and were always considered a target.

Each trial was composed of 12 stimuli. The CT appeared in half of the trials, which were randomized in blocks of 16 trials for each load condition. Each block included 8 trials with the PT and 8 with CT-only. The load condition was balanced between participants. Each subject was presented a total of 224 trials (2 load × 7 modalities × 2 (with/without PT) × 8 repetitions). Trials in which the participants responded in under 100 ms (premature responses) were considered errors. Four familiarization trials were presented before the experiment. Participants provided a feedback on the condition's perceived difficulty.

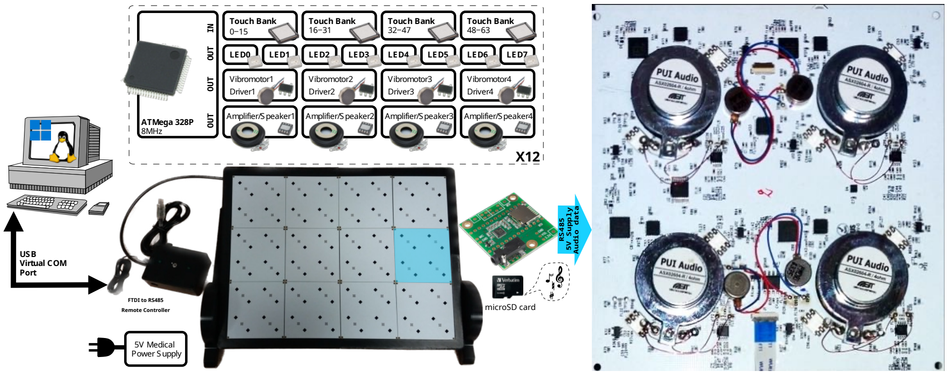

Fig. 2. Block scheme of the TechPAD. The system comprises 12 all equal tiles that are interconnected using an RS 485 interface. Each submodule comprises a dedicated IF/SM sub-system that provides bus capability and generates audio sounds to be broadcast by the speakers.

III. RESULTS AND DISCUSSION

We analyzed accuracy (*errors/total targets*) and reaction times (RTs). Data were analyzed using R (4.2.2 with lme4 1.1.30). Raw data are available at the doi:10.5281/zenodo.7651329. No significant differences were found concerning the accuracy among the sensory modalities neither in LLC nor in HLC. We used non-parametric analysis since RT for both CT and PT were not normally distributed (Anderson Darling test, CT: A=223.27, p<2.2*e*-16; PT: Anderson Darling test, A=18.043, p<2.2*e*-16). We verified that the load manipulation was successful since average RTs for CT were significantly higher in HLC compared to LLC (Wilcoxon signed rank exact test, V=406, p=7.5*e*-09). In accordance, 25 participants reported that they had perceived the HLC as more difficult.

We compared which modality provided better RTs in detecting the PT in the two load conditions. We hypothesized that multimodal stimuli would provide faster RTs than unimodal ones. A Generalized Linear Mixed Models (GLMMs) was used due to its performance over ANOVA in the analysis of RTs [18]. We used a Poisson family GLMM with log link. The model included the intercept, the load and the peripheral modality as within factors, and their interactions. The contrasts were corrected with Tukey's HSD test. Results are shown in Fig. 4. Both in LLC and HLC, unimodal stimulations presented higher RTs, with Haptic (H) associated with the worst performance (LLC: H-A<0.047, H-V<1*e*-05, H-HA<3.1*e*-06, H-VA<0, H-VH<0, H-AVH<0; HLC: H-A<0.0075, H-V<1.3*e*-13, H-HA<7.2*e*-09, H-VA<0, H-VH<0, H-AVH<0), while AVH had the fastest responses (LLC: AVH-H<0, AVH-A<0, AVH-V<0, AVH-HA<0, AVH-VH<0.032; HLC: AVH<0, AVH-A<0, AVH-V<0, AVH-HA<0, AVH-VH<4*e*-09). Interestingly, AVH did not significantly differ from VA (LLC: AVH-VA<0.8; HLC: AVH-VA<1). Such results are consistent with the literature, in which multisensory stimuli enhance RT regardless of perceptual load, even though performance is not entirely immune to a load effect [2, 3]. In our study, an exception to this trend is HA. HA RTs in LLC did not significantly differ from A (p<0.68) nor V (p<1), while in the HLC they did not significantly differ from A (p<0.34). Furthermore, they were significantly higher than RTs to V (p<0.048). Such results would suggest that multimodal stimulation is not always beneficial for detection when compared to unimodal stimulation but that their relationship depends on the type of sensory modality. In our task vision seems the most efficient sensory modality. These results are consistent with previous studies (such as [19]), suggesting that for a spatial task in a collocated setting, V may be more accurate than H and VH

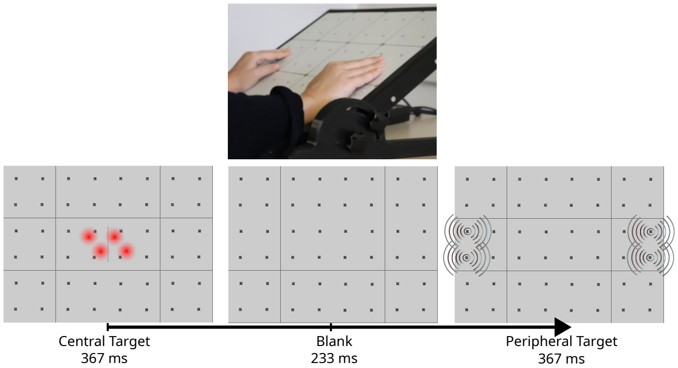

Fig. 3. Part of a trial with a central target stimulus followed by a peripheral auditory target stimulus. Participants sat 50 cm from the TechPAD, with their hands on the lower part of the device, equally distanced from its center.

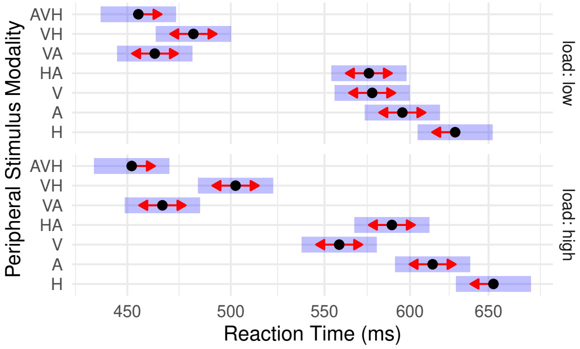

Fig. 4. Post-hoc tests of the estimated GLMM model. Black dots are the means and blue boxes represent the Confidence Intervals. Within each load (high, low), red comparison arrows are based on Tukey's HSD Test; two estimated marginal means differ significantly if, and only if, their respective comparison arrows do not overlap.

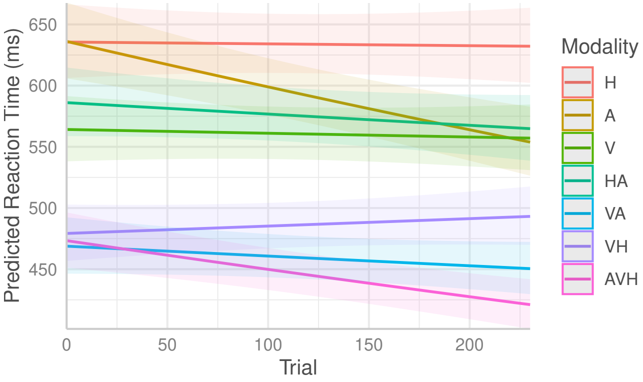

Fig. 5. GLMM RT prediction by modality and trial number. Shadows represent the Prediction Interval. Only A and AVH modalities have a significant effect on the RTs. The negative slopes represent an improved RT over time for those two modalities.

perception. Nonetheless, this result may be due to the type of task: as the central task is essentially visual, a congruent stimulus (V) may be more effective than non-congruent (AH) stimuli in driving attention.

Finally, observing the trend of performances during the task, a specific training effect emerged (see Fig. 5). In a GLMM with the intercept, load and trial, there is no global effect of the trial, but there are significant interactions between the trial number and the peripheral modality in A ($p<0.0025$) and AVH ($p<0.0079$). No conclusive evidence can be drawn from these data, but it is worth further investigation as it could open up to possible practical implications for (re)habilitation (e.g., supporting the choice of the most effective sensory modality to train in sensory deprivation conditions).

IV. CONCLUSIONS

New technologies can be helpful in expanding the knowledge on the role of different sensory modalities in neurodevelopment and in adopting evidence-based intervention strategies. The TechPAD is able to provide different multimodal stimuli, as well as quantitatively measure parameters such as RT and accuracy. Thus, it could be a useful device for developing interactive tasks. The TechPAD was used for the first time in the present work and promised to be a valuable assessment tool for attentional and perceptual skills and other cognitive domains, such as memory and spatial competencies. Further studies are needed, especially clinical trials, to validate its potential for the (re)habilitation in children and adults with or without sensory impairment.

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