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Dr-MUSIC: An Effective Device for Investigating Multisensory Mechanisms during Development with EEG recordings*

A. Bollini[1], H. Vitali[1], M. Crepaldi, A. Parmiggiani, C. Campus, C. Lorini, M. Gori

***Abstract*— From birth, we are continuously exposed to multisensory stimuli that we learn to select and integrate during development to perceive a coherent world. To date, there are no optimal solutions to investigate how auditory, visual and tactile signals are integrated during EEG recording in infants and children. The present work aims to introduce Dr-MUSIC, a novel multisensory device with EEG-compatible timing and an attractive design for children. It is composed of audio, visual, and tactile stimulators arranged in the form of a couple of chubby dragons that can simultaneously provide selectable uni-, bi-, or tri-modal information. We first validated the system's EEG compatibility in 8 adults by implementing an audio-tactile oddball task during a high-density EEG recording. Then, we replicated the same task in a couple of toddlers to validate the device's usability for young children. The results suggest that the system can be effectively used for setting new experimental protocols to understand the neural basis of multisensory integration in the first years of life.**

***Clinical Relevance*— The amusing design and the possibility of changing the stimulation's characteristics (i.e., light, sound, and vibrotactile features) make it attractive in children with and without sensory impairments. Therefore, Dr-MUSIC could be used to investigate multisensory development and related neural correlates in typical and atypical children to design new early rehabilitation protocols.**

I. INTRODUCTION

The first years of life are crucial for developing neural processing of multisensory information. Constantly, the external environment provides a deluge of sensory information that we acquire through different sensory systems. These signals are captured by our peripheral cells and travel through the neural system to arrive in the brain and the cerebral cortex. At birth, our brain cannot completely integrate all the signals coming from different senses, and therefore, it needs to learn to manage redundant information during development to perceive a coherent world. In some clinical disorders, the absence of one sense impacts how the external environment is acquired, for example, blindness and deafness. Congenital conditions compromise the ability to integrate multisensory information and perceive space, as in visual system disorders [1], and time, as in hearing system impairments [2]. These findings suggest that early life plays a crucial role in constructing neural networks involved in multisensory integration (MSI).

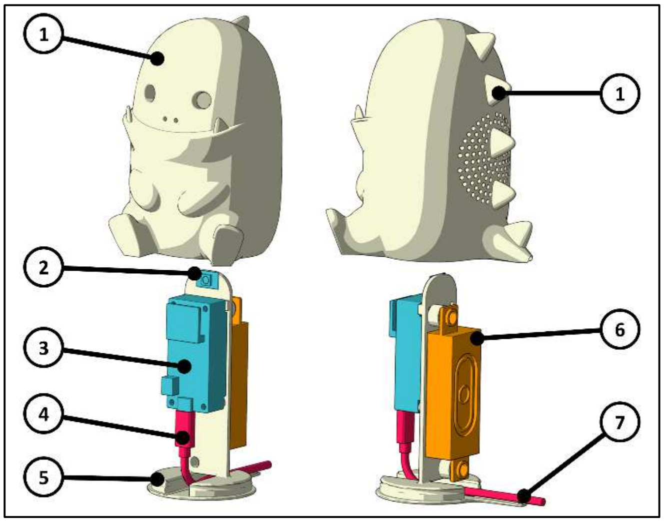

Fig. 1 CAD view of the device. The figure shows an exploded view of the device and its components: the outer shell (1), the LED (2), the electronic boards stack (3), the USB cable (4), the support structure (5), the loudspeaker (6) and the wire exit (7).

In this context, we present *Dr-MUSIC (DRagons for MUltisensory Stimulation in Infants and Children)*, a novel technological solution that can be used to assess the first developmental stages of MSI mechanisms during electroencephalographic (EEG) recordings. The EEG is a not invasive neurophysiological technique and is the best solution to investigate the brain possessing in infants and children. To date, no technological devices provide specific unimodal, bi-modal, or tri-modal audio, visual, and tactile stimulation with EEG-compatible timing and an attractive design for children. Dr-MUSIC is composed of a funny couple of chubby dragons that can provide uni-, bi-, or tri-modal information simultaneously. To the best of our knowledge, only some solutions can provide up to tri-modal stimulations in a unique device [3], [4], but not all give the possibility to change the characteristics of the stimulation. In our device, the color and the intensity of the light, the sequence and the intensity of vibration, and the type of sound can be changed according to the practical necessities, as well as the duration of the stimulation. The amusing design makes it easier to use in young participants, and the possibility of changing the stimulation's characteristics makes it attractive even in children with sensory impairments. Therefore, Dr-MUSIC represents an effective, innovative technological system for investigating cross-modal and multisensory development in a more ecological and playful environment in infants and children during EEG recordings. Dr-MUSIC allows to

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[1] Joint first authors.

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A.B., M.C., A.P., C.C., C.L., and M.G. are with Istituto Italiano di Tecnologia, Genoa, Italy (corresponding author to provide phone: +39 0108172232; email: alice.bollini@iit.it).

H.V. with Istituto Italiano di Tecnologia, and with Università di Genova, Genoa Italy

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simulate many situations in which information presented to one sense may be irrelevant or even conflict with the information presented to a different sensory modality. Indeed, detecting and filtering out these oddball stimulations in these situations plays a key role in developing efficient functioning.

To evaluate the effectiveness of the technology, here we first validated the device's EEG compatibility during an audio-tactile oddball task (i.e., different stimulations unexpectedly deviating from a predictable sound sequence) during a high-density EEG recording in a group of sighted adults. Then, we replicated the same task in a couple of toddlers to validate the device's usability for young children.

II. METHODS AND MATERIALS

A. *Dr-MUSIC Implementation*

We will here briefly present the system's design from a mechanical and electronic point of view.

a) Mechanical Design

The mechanical design of the device was conducted with the PTC Creo Parametric 8.0 CAD platform, combining the traditional parametric feature-based approach with free-form modeling for the external surfaces. It was decided to shape the device's exterior as a chubby dragon with a wide mouth and large eyes to prompt a friendly appearance (deemed necessary for experimenting with young participants) while hiding the electronics in a compact form factor. The final design is represented in Fig. 1. As can be seen, all the electronics are assembled onto a central support part. The outer cover also connects to the central support part with two screws in its lower part. This design presents the additional advantage of separating the outer covers from the internal electronics. Therefore, it simplifies changes to the shape of the external covers if user testing reveals this as necessary. In the current design, the dragons' tails were exploited for creating guided wire exits for the electronics wiring. The covers were made by additive manufacturing (AM, also known as 3d printing) with a 3D Systems PRO SLS 6100 selective laser sintering (SLS) machine. The material used was white Polyamide 12 (PA12 - Nylon). The use of AM is advantageous in developing devices of this kind as it allows considerable cost and development time savings and, in turn, facilitates design iterations.

b) Electronic and Firmware Design

Fig. 2 shows the electronic block scheme of Dr-MUSIC, with a high-level schematic description of the software. The system has been conceived here by exploiting the commercially available Adafruit/Arduino development boards for ease of implementation and to enable rapid prototyping toward a fully engineered solution. The system is a programmable multisensory output generator capable of playing three types of outputs, audio, visual and vibrotactile. It comprises a main unit (`Adafruit Feather M0`) capable of handling communication with a personal computer (PC) through a Virtual COM port emulated using a USB physical layer. This way, the user can implement high-level software using any development environment that can read and write a Universal Asynchronous Receive and Transmit (UART) interface, such as Matlab (as shown in the figure) or alternatively Python. Besides handling communication, the main unit is responsible for interacting with the peripherals to implement the multisensory outputs with accurate timing. Programmable audio outputs are here made possible by using an `Adafruit Music Maker` module, interfaced with the Feather M0 using a Synchronous Peripheral Interface (SPI). The module drives a single miniature speaker with 8Ω impedance capable of outputting 1W power. It comprises an microSD interface to store audio data in the form of PCM Wave files or compressed MP3 audio. The vibrotactile feedback is implemented using an Inter-Integrated Circuit (I2C) vibrotactile driver DRV 2605, which can implement various default vibrotactile profiles or asynchronous duty cycling vibration based on the main unit commands. In this application, we have used a 12kRPM DC Vibromotor that is compatible with the standard 3.3V regulated voltage available in the main unit. We have included an RGB LED directly interfaced with a single wire to the Feather M0 microcontroller to implement the visual stimulation.

Dr-MUSIC needs to be capable of rapidly outputting multisensory feedback, with particular emphasis on audio signals. Considering the presence of three types of possible stimulus (audio, visual and vibrotactile), at the software level, it is ideally possible to implement all possible hybrid combinations, where a single command from the PC can trigger heterogeneous types of outputs (e.g., audio/tactile, tactile/visual, visual/audio). Here we have implemented specific commands to trigger multiple events without transmitting multiple serial commands, thus keeping the jitter

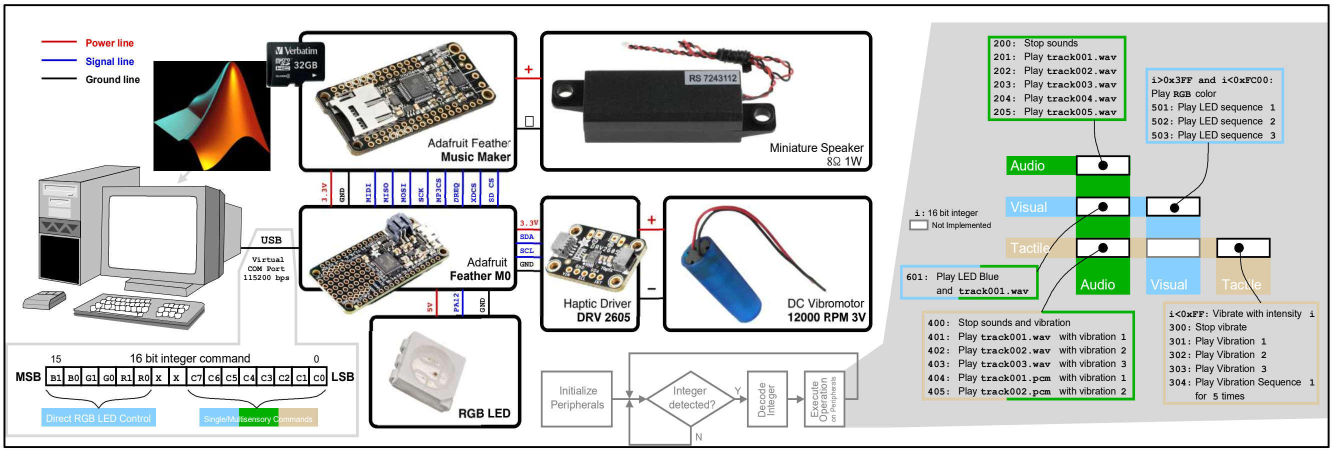

Fig. 2 Block scheme of Dr-MUSIC with detail on the components used, and scheme of the internal firmware implementation. The device is capable of performing accurate multisensory stimulation thanks to the use of integer-based dedicated commands.

of the events below 1ms. The internal microcontroller can run multiple tasks faster than subsequent transmissions on the USB bus. To maintain ultimate simplicity in parsing the incoming message from the PC, we have based the transmission on only a 16-bit integer. Such 16-bit integer command indeed is a very flexible and fast solution compared to more complex signaling schemes that imply more complex decoding and parsing mechanisms, hence favoring real-time operation thanks to the possibility of fast decoding (shift and comparisons). Specific multisensory commands are implemented using the low byte (`C7−C0`), while the higher byte most significant bits are used to implement 64 color values with the RGB LED. The bits marked with `X` are not used here and can be used to expand the functionalities of the device further.

We have divided the trigger functionality based on the value of the incoming command *i*. A command in the `200−299` integer range refers to audio stimulation. Here, we have implemented 5 possible cases, where `200` stops all sounds and `201−205` plays specific Wave files in the SD memory of the Music Maker. Integers below `127` and in the range of `300−399` are dedicated to tactile stimulation. In particular, for $i <$ `127`, continuous tactile stimulation is outputted with intensity proportional to *i*. For $i =$ `300`, tactile stimulation is stopped, while for `301−304,` specific tactile sequences can be played. The range `500−599` is dedicated to playing visual sequences, and if the high byte part is triggered, the 64 possible colors are outputted. To trigger multiple outputs simultaneously, we have implemented ranges `500−599` and `600−699` to trigger audio/haptic and audio/visual stimulation. Notably, implementing a fallback command to stop stimulation (consider 200 or 300) is a wise choice to avoid potential issues in the implementation of the high-level software control, especially during an initial development phase, thus avoiding power cycling the device to reset its state. The firmware has been implemented using the Arduino Integrated Design Environment (IDE) in C++ using a bare metal approach to maintain the device's maximum responsiveness following the command's reception. After peripheral initialization at power-on reset, the main loop simply waits for a new integer input to be decoded, and if this occurs, it implements a selection on its value to call back the specific methods to access the peripheral buses and set the desired stimulation sequence.

B. Experimental Protocol

We implemented an audio-tactile oddball paradigm in two experiments to validate our device: in the first experiment, we tested a group of 8 adults (30.74 y.o. ±5.44, 4F). Then, we tested the device's compliance in two toddlers (35 m.o., 1F) in a second experiment. All participants were recruited from the local contacts of Genoa. The local ethics committee (ASL3 Genovese) approved the study, and all participants or their parents signed written informed consent forms under the Declaration of Helsinki.

a) Experimental Procedure

EEG data were recorded with EGI (Electrical Geodesics, Inc.) collecting system with 129 electrodes, using Cz electrode as the reference, acquired at 1000 Hz. The participants' heads were measured for proper EGI net placement. The net was then placed on the head, using sponges soaked in a salt-water solution. Participants were comfortably seated with the Dr-MUSIC device in front of them, holding in their right hand the small dragon for tactile stimulation (Fig. 3A). We employed a passive audio-tactile oddball paradigm while participants watched a silent movie (Shaun the Sheep). The audio-tactile oddball consists of 70% standard audio stimuli (750 Hz beep sound, command 201), 10% oddball audio stimuli (blazer sound, command 202), 10% oddball tactile stimuli (middle-intensity vibration, command 100), and 10% oddball audio-tactile stimuli (a combination of audio and tactile oddball stimuli, command 503). All the stimuli had the same duration of 250 ms (Fig. 3B). The task consisted of 600 trials in total, presented randomly with a minimum of one standard stimulus before every oddball stimulus. Participants were instructed to sit still throughout the experiment. Participants were asked to watch the movie and ignore the stimuli coming from the Dr-MUSIC, with a trained experimenter seated behind monitoring them.

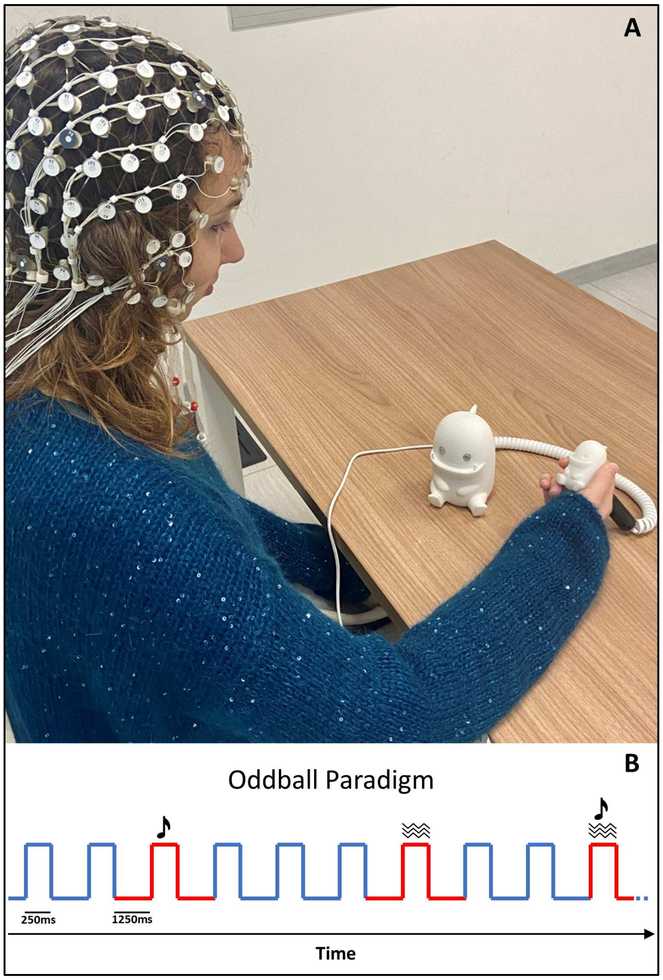

Fig. 3 Experimental procedure of the audio-tactile oddball. (A) The figure shows an adult participant during EEG recording. (B) A representation of paradigm sequence.

b) EEG Processing

The EEG signal was processed using custom scripts that combined the EEGLAB [5] and Fieldtrip [6] toolboxes. The continuous EEG signals were filtered between 1 45 Hz (zero-phase Butterworth filter, fourth order) and then downsampled

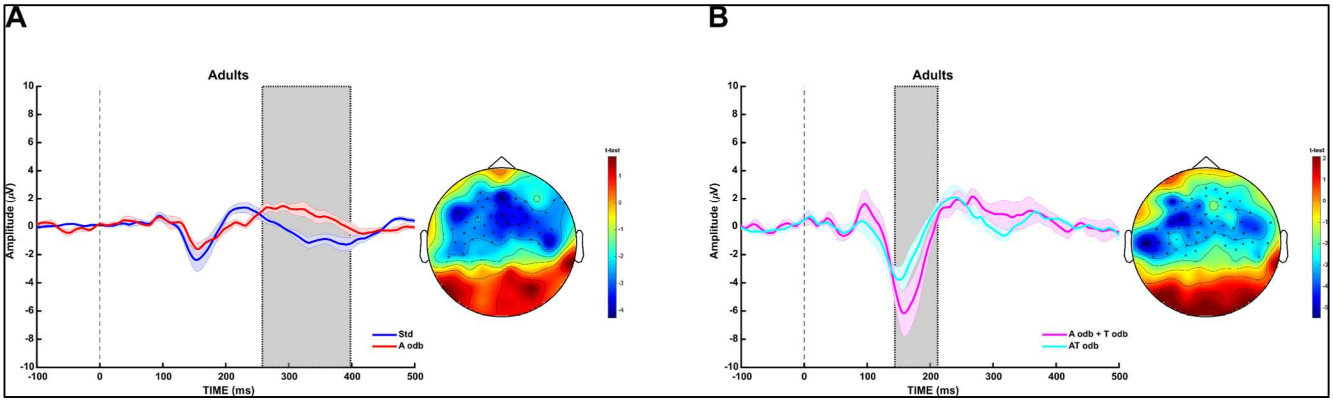

Fig. 4 ERP results in the adult's experiment. The left panel (A) shows the ERPs of the standard (blue) and oddball sound (red); while the right panel (B) shows the ERPs in the additive model, comparing the auditory + tactile oddball stimuli (magenta) with the audio-tactile oddball (cyan). The ERPs are averaged across central electrodes. The shade bands represent the SE. The light gray areas highlight the time windows of the significant differences between the conditions. The maps represent the topographical distribution of the significant t-values in the comparison of the two conditions; the crosses represent the electrodes included in the significant negative clusters.

at 500 Hz. To remove transient stereotypical (e.g., eye blinks) and non-stereotypical (e.g., movement or muscle bursts) high-amplitude artifacts, we applied the artifact subspace reconstruction (ASR) method [7]. Data were divided into epochs from -1000 ms to 1000 ms after stimulus onset. The segmented data were subjected to independent component analysis (ICA) to clean further EEG data. To remove the artefactual components, we used a combination of metrics and manual inspection based on topography, latency, amplitude, and trial distribution. Then, the noisy channels previously removed were interpolated and data were referenced to the average of the left and right mastoids (E57 and E100 electrodes). Lastly, to obtain Event-related Potentials (ERPs), epochs were reduced to -200 before and 500 ms, applying a baseline correction of 200 ms before the onset of the stimulus.

c) *ERPs Analyses*

We ran two analyses to test the validity of the Dr-MUSIC device for investigating multisensory and attentional mechanisms. First, we tested the attentional mechanisms in each group's grand averages by comparing the standard and oddball sounds. Second, we investigated the multisensory effect in attentional processes in our oddball stimuli using the *additive criterion model* [8]–[10], where the MSI effect is defined as a non-linear summation of the response to multisensory stimuli (AT), differently from the sum of unisensory stimuli (A+T); these effects can be supra- or sub-additive. To test these processes, we employed two-tailed cluster-based permutation t-tests in all channels [11] on the time window between 0 to 500 ms after stimulus onset with 1000 random sets of permutations. This non-parametric method allows for multiple comparison testing when computing statistics across multiple channels and time points without making any assumptions about the specific time windows or scalp locations where differences may arise. Moreover, this approach has been tested to provide a correct type 1 family-wise error rate (FWER) al in the case of small sample sizes [12].

III. RESULTS AND DISCUSSION

A. *Audio-tactile Oddball in Adults*

We tested the modulations induced by an auditory, tactile, and audio-tactile oddball stimulus in the ERPs of adult participants. In the first analysis, we tested the attentional processing by comparing the oddball with standard sound. As a result, we found similar results to those reported in the literature [13]. The cluster permutation analysis on ERPs revealed a negative cluster ($p < 0.001$), demonstrating differences between the standard and oddball stimulus responses. The cluster spread in time and space, from 258 ms to 392 ms, over fronto-central channels (Fig. 4A). The difference in this window is in line with the literature where rare sounds deviating from a standard sequence induce a change in the ERP response. P2 (250-300 ms) and P3 (300-400 ms) are the two ERP components involved in this attentional process. Particularly in the P2 domain, an oddball sound induces a mismatch negativity (MMN) represented by a negative peak generated after the P2 [13]. In the second analysis, we investigated the influence of MSI on attentional processing. Here we applied the additive model ($A+T \neq AT$) to test the interaction between unimodal and multimodal oddball stimuli. After the cluster permutation analysis, we found a negative cluster ($p < 0.001$) between 144 and 212 ms over the fronto-central channels. This cluster demonstrated the presence of a non-linear interaction between unimodal and audio-tactile stimuli in the N1 domain (150-200 ms), revealing the presence of the MSI effect. This effect was sub-addictive, as reported in other MSI studies [9], [14], [15].

B. *Audio-tactile Oddball in Toddlers*

In this experiment, we tested the audio-tactile oddball in a couple of toddlers to verify Dr-MUSIC usability in such young children and their compliance with the experimental session. Children interacted with the device for the entire experimental session (roughly 40 minutes), keeping in their hands the little dragon. From the EEG analyses, we found a negative cluster ($p < 0.001$) between 298 and 318 ms over central channels (Fig 5), meaning the presence of attentional-orientating processing in the MMN domain, as reported in similar research [16]. Finally, we did not report any significant cluster when testing the additive model in uni- and multi- modal oddball stimuli.

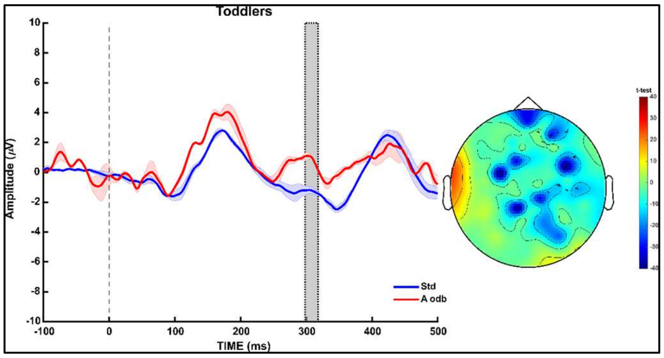

Fig. 5 ERP results in the toddler's experiment. The figure shows the ERPs of the standard (blue)and oddball sound (red). The ERPs are averaged across central electrodes. The shade bands represent the SE. The light gray areas highlight the time windows of the significant differences between the conditions. The maps represent the topographical distribution of the significant t-values in the comparison of the two conditions; the crosses represent the electrodes included in the significant negative clusters.

The absence of MSI effect was hypothesized as it has been demonstrated that this process develops in later stages [17]. Future studies with more participants will be necessary to confirm this result.

IV. CONCLUSION

This work introduced an innovative, effective technological system suitable for investigating cross-modal and multisensory development in young participants during high-density EEG recordings. Our experiments validated the use of Dr-MUSIC during EEG recording in adults and toddlers, detecting the change in brain activity with unattended oddball stimuli, as reported in the literature. Moreover, an audio-tactile MSI effect in the N1 domain was reported in adults but not in children participants. These findings highlighted the importance of investigating the neural correlates of the MSI processes while the brain matures to define the developmental steps necessary for an efficient MSI. In the future, we will use our system in typical and sensory-impaired children of different ages to determine the developmental trajectory of MSI neural correlates. The aim is to discover when developmental divergence occurs in sensory-impaired children to design new early rehabilitation interventions.

ACKNOWLEDGMENT

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