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Combination of motor, sensory and affective tasks in an EEG paradigm for children with developmental disabilities

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ABSTRACT

Individuals with neurodevelopmental disorders exhibit overlapping emotional, somatosensory and motor deficits. Although brain processes underlying these impairments have been extensively studied in a separate way, the brain interaction of these inputs is an innovative line of research. Here we present a new EEG methodology for exploring the interactive brain activity of sensorimotor and affective stimuli. The task consists in presenting affective stimuli of different modalities (e.g. affective pictures, affective touch) while simultaneously an arthromotor performs passive joint movements, unseen by the participant. Participants were then required to press one of two buttons to indicate if their joint position agreed with a picture shown in a screen. Pilot data of electroencephalography recordings revealed distinct somatosensory event-related potentials (SEP) when movement was subsequent to affective stimuli, compared to neutral stimuli, as well as a differentiation of SEPs for different neurodevelopmental conditions. Behavioral responses further showed that children with cerebral palsy had more errors to identify their hand position when they were exposed to affective stimuli. This paradigm is a valuable tool to explore the modulative influence of emotion in the sensorimotor brain processing of different populations with joint emotional and sensorimotor impairments, such as children with neurodevelopmental disorders or patients with stroke.

- This method allows exploring the interaction between affective and sensoriomotor inputs in an EEG paradigm.

Specifications table

Subject area:	Neuroscience
More specific subject area:	Electrophysiology, neurodevelopmental disorders
Name of your method:	EEG - emotion/sensorimotor modulation
Name and reference of original method:	
Resource availability:	github.com/FMS205/Arthromotor/

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Background

Abnormal sensory perception, motor disfunctions and emotion dysregulation are major problems in individuals with neurodevelopmental conditions [1]. Sensorimotor brain processing in neurodevelopmental conditions is characterized by particular features such as alterations in the cortical thickness of sensorimotor structures, atypical thalamic functional connectivity or abnormal sensorimotor integration [2-4]. On the other hand, diminished ability to process affective emotional stimuli, reflected in abnormal event-related potentials and brain networks connectivity, has been reported, for example, in children with ADHD, disruptive behavior, cerebral palsy and autism [5-8].

The emotion-related brain modulation of sensorimotor inputs is already extensively admitted in neurotypical individuals. According to this research, multiple studies on muscle activity, body posture or somatosensory processing have demonstrated that sensorimotor brain processing can be modified by emotionally-charged stimuli as, for instance, the viewing of affective pictures [9-11]. The affective modulation of sensorimotor behavior and brain processing has also been demonstrated in other populations, such as patients with chronic pain [12-14]. In this context, emerging scientific research is starting to explore the relationships between the sensorimotor and emotional systems in individuals with neurodevelopmental conditions. For instance, studies with autistic individuals have shown a reduced recruitment of the somatosensory system during the embodiment of emotional facial expressions or social touch [15-16]. As another example, EEG parameters, such as S1 functional connectivity or beta oscillatory activity, have been distinctively modulated by emotional faces depending on the presence of autistic traits [17-18]. Our research aims at adding new evidence to this innovative research line, exploring the reciprocal influence of sensorimotor and emotional brain processing in individuals with neurodevelopmental conditions.

To address this issue, we have developed a method of multivariate measurement, integrating multiple tools to gain a comprehensive understanding of responses to concurrent stimuli. The system incorporated an arthromotor for assessing proprioception in children with and without neurodevelopmental disorders, by inducing controlled and precise passive wrist flexion and extension movements. This tool, coupled with EEG recordings and the presentation of visual and tactile affective stimuli using Matlab-programmed software, facilitated a thorough evaluation of the emotional modulation of sensorimotor perception within an interactive environment. A pilot study with 2 children with cerebral palsy, 2 children with autism spectrum disorder and 1 child with typical development underscore the success of the methodology in integrating diverse measures for the study of brain interaction of emotional and sensorimotor perception in children, and can be implemented in other complex conditions. As a future direction, expanding the range of stimuli and measures is proposed to further enhance the evaluation and comprehension of these complex processes.

Method details

This study introduces a novel, non-invasive add-on to the existing EEG recording system, specifically designed to investigate the interaction between sensorimotor and emotional brain processing in individuals with neurodevelopmental disorders. Our methodology involves an innovative task that combines affective stimuli with passive joint movements induced by an arthromotor. The task consists of presenting affective stimuli in two modalities—visualizing affective pictures or experiencing affective touch—while the arthromotor performs passive wrist movements that are unseen by the participant. Participants are then required to press one of two buttons to indicate whether their perceived joint position agrees with the picture shown on a screen.

This experimental setup integrates seamlessly with traditional EEG recording systems by simply adding time-marked events to the EEG signal, corresponding to the various stimuli and participant responses. This integration ensures that the system remains non-invasive, maintaining the standard EEG recording procedure while significantly enhancing its capability to study complex brain interactions.

As in most EEG experiments, the experimental setup clearly distinguishes two separate zones: the Study Zone and the Control Zone. The Study Zone, detailed in Fig. 1, includes the participant setup with the arthromotor and the EEG recording apparatus. The Control Zone encompasses the software components used in the study, including the primary MATLAB program, microcontroller code, and an overview of the EEG registration software. Following the description of the Study and Control Zones, the assembly chapter will provide detailed instructions on how to set up the arthromotor and the entire system. This includes step-by-step assembly instructions, connection schematics, and a bill of materials required for replication of the setup. By providing comprehensive details, this chapter ensures that the methodology can be accurately replicated, facilitating further research into the interaction between sensorimotor and emotional brain processing in various populations.

Description

The Study Zone encompasses the environment where EEG data is collected, designed to facilitate the simultaneous presentation of affective stimuli and the induction of passive wrist movements. This zone is shown in Fig. 1, highlighting the positions of the key components: EEG electrodes, the participant, and the arthromotor. The figure is divided into two parts: a virtual representation of the setup (Fig. 1A) and a photograph showing the actual setup with a participant (Fig. 1B).

In this setup, the participant is seated comfortably with EEG electrodes positioned on their scalp to record brain activity. The Presentation Screen (Element 1) is placed directly in front of the participant, displaying the visual stimuli. A vision covering (Element 2) is used to block the participant's view of their own hand and the arthromotor, ensuring that the movement remains unseen and does not influence the participant's proprioceptive responses.

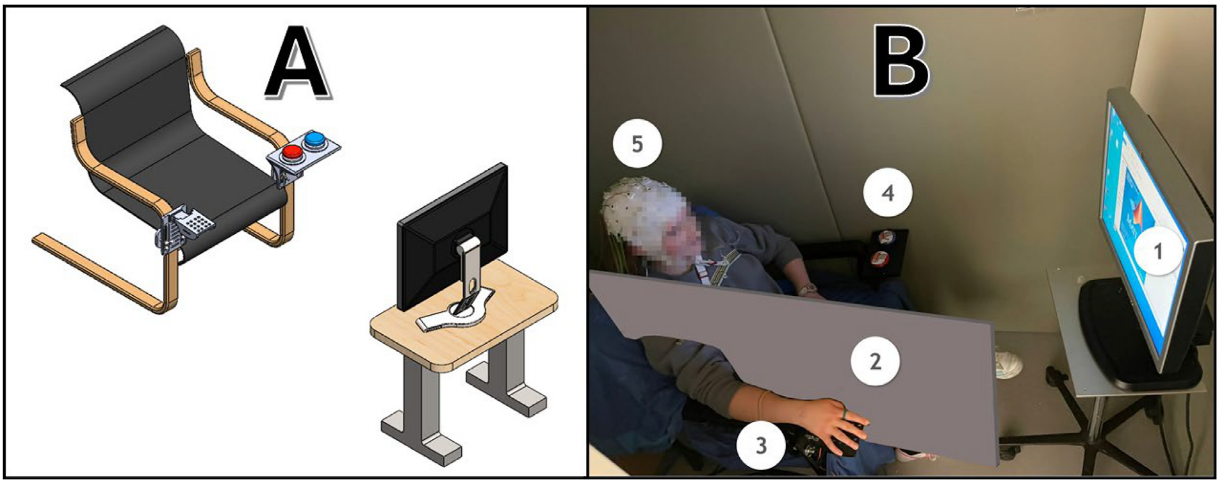

Fig. 1. Virtual Study Zone Setup (A) and photography with an actual patient (B), specifying the different elements of the experiment: (1) Presentation screen; (2) Vision covering; (3) Mechanical arthrormotor device; (4) Proprioception response buttons; (5) Participant EEG recording.

The Mechanical Arthromotor Device (Element 3) is positioned to perform passive wrist movements on the participant's hand. This device is crucial for introducing controlled, repetitive wrist movements while the participant is engaged with the visual stimuli presented on the screen.

Proprioception Response Buttons (Element 4) are placed within easy reach of the participant. These buttons are used by the participant to indicate whether their perceived joint position aligns with the actual arthromotor's position, allowing the researchers to record their proprioceptive responses.

Finally, the Participant EEG Recording (Element 5) setup includes the EEG cap and the associated recording equipment. The EEG system is synchronized with the event marking system, which adds time-stamped markers to the EEG signal corresponding to the onset of visual stimuli and the initiation of arthromotor movements.

The Control Zone is the operational hub of the experiment, housing the main control computer and the data collection systems. This area is responsible for managing the experimental protocols, synchronizing the stimuli with the EEG recordings, and storing the collected data for subsequent analysis. In the Control Zone, we utilize several software components to ensure the smooth execution of the experiment. The primary software used is MATLAB, which orchestrates the entire experimental protocol. MATLAB is responsible for presenting the visual stimuli, sending commands to the arthromotor, and marking events on the EEG signal to ensure precise synchronization. In addition to MATLAB, we use custom code running on an ESP-32 microcontroller to control the mechanical arthromotor device. This code manages the servo motor responsible for inducing passive wrist movements. The EEG recording software is another critical component in the Control Zone. It captures and stores the EEG data, including the event markers added by the MATLAB script. This setup allows for detailed analysis of the brain's response to the combined sensorimotor and emotional stimuli.

Matlab program

The central software tool used for data acquisition, event coding, and preliminary analysis. Matlab scripts are responsible for sending event signals to the EEG system in real-time. The MATLAB code for the arthromotor system is designed to coordinate passive wrist movements while simultaneously recording EEG data. Below is a detailed explanation of the code's functionality, aligned with each step of the provided flowchart in Fig. 2.

The script begins by initializing MATLAB's memory space, ensuring a clean slate by clearing any existing variables and the command window. This step is crucial to avoid conflicts from previous sessions and ensure the system starts from a known state. Following this, the parallel port is configured using MATLAB's **io32** function, establishing communication with the EEG recording system. This setup allows MATLAB to send event markers to the EEG system, enabling precise synchronization of events with the EEG data.

Next, the serial port is configured to communicate with the ESP-32 microcontroller, which controls the arthromotor. This involves setting the appropriate COM port and baud rate, ensuring reliable communication between MATLAB and the ESP-32. The initialization phase also includes setting up commands necessary for operating the arthromotor, ensuring that it is ready to receive instructions and perform the required movements. These initialization commands are sent to the arthromotor via the serial port.

The experiment's visual stimuli are then loaded into MATLAB. Images used in the experiment are read from a specified directory into MATLAB's workspace. Along with image loading, experimental parameters such as the duration of image display and the number of trials is configured to define the structure of the experiment.

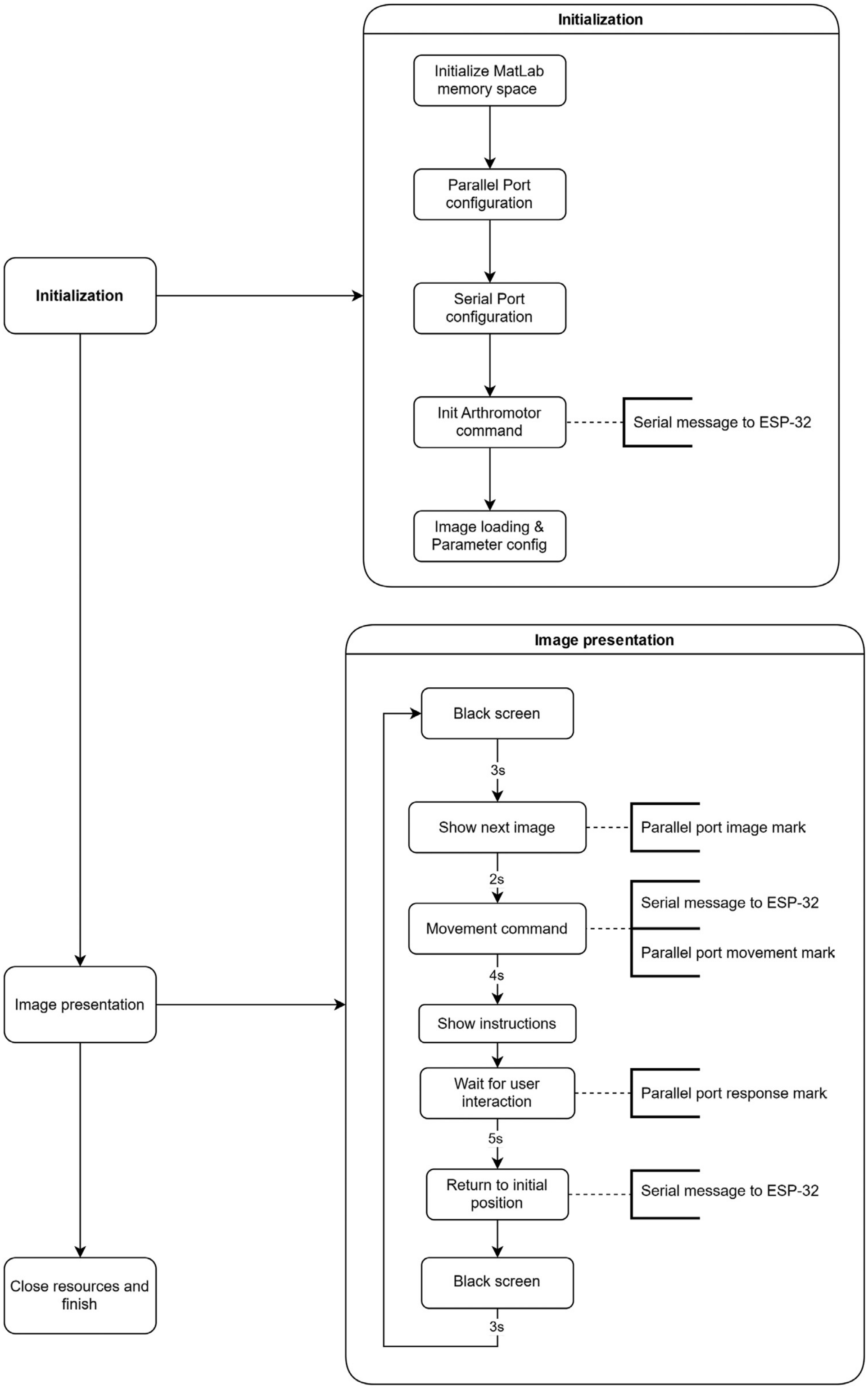

Fig. 2. Matlab flow chart.

During the image presentation phase, a black screen is first displayed for a few seconds before each image. This step resets the visual field, preparing the participant for the next stimulus and ensuring a clear visual transition. Following this, the next image in the sequence is displayed for the duration specified in the experimental parameters. This image acts as a visual stimulus for the participant, with each trial presenting a different image or set of images. These images may consist in affective pictures of different valence, presented randomly or in blocks, or in a black screen with a fixation cross that indicates the beginning of the tactile stimuli (affective / non-affective touch) to the examinator.

Two seconds into the image presentation, a command is sent to the ESP-32 microcontroller via the serial port to initiate the arthromotor movement. This is followed by a 4-second pause to allow the participant to process the visual/tactile stimulus and for the arthromotor to complete its movement cycle. Subsequently, instructions for providing the proprioception response are shown on the screen, and the code waits for user interaction with the response buttons for up to 5 s. After that timeframe, a command is sent to the microcontroller to return the servo to its initial position. While the motor is returning, the black screen is displayed again for 3 s to prepare the participant for the next stimulus, ensuring smooth transitions and maintaining consistency in the experimental conditions.

The entire image presentation sequence is repeated for the specified number of trials, ensuring each trial follows the same structure. By following these steps and using the corresponding MATLAB code (available on GitHub), you can replicate the study and ensure accurate synchronization between visual stimuli and arthromotor movements while recording EEG data.

ESP-32 code

Custom firmware has been developed for the ESP-32 microcontroller to handle the arthromotor's behavior. The microcontroller code for controlling the servo movement in the arthromotor follows a structured approach to ensure precise and timely wrist movements. A visual representation of the setup and main loop processes, as well as the handling of various interrupts is illustrated in the flowchart of the ESP-32 firmware (Fig. 3). This diagram helps to clarify the workflow and the interactions between different components of the firmware.

Initially, the setup routine configures the necessary parameters, initializing the servo motor and setting up communication protocols, such as Bluetooth and Serial. This foundational setup ensures that the system is prepared to handle incoming commands and control the servo motor effectively. The main loop continuously monitors for any incoming messages or interrupts that could alter the motor's behavior. Upon receiving a Bluetooth message interrupt, the code decodes the message, updates the program flags, and returns to the main loop. Similarly, when a Serial message interrupt is detected, the message is read and stored, followed by a return to the main loop. In the event of a timer interrupt, the code increments an interrupt counter and processes the timer-specific logic before rejoining the main loop. Each type of interrupt is managed in a dedicated segment of the code, ensuring that the system can handle multiple forms of input without losing track of its primary function. This modular design not only enhances readability and maintainability but also allows for future expansions or modifications with minimal disruption to the existing structure. Throughout this process, the system maintains real-time control over the servo motor, adjusting its position based on the decoded commands. This ensures that the arthromotor provides accurate and consistent wrist movements, which are vital for the study's goals. The detailed implementation of this logic is provided in the accompanying code repository, which offers full visibility into the exact commands and sequences used to achieve this functionality.

EEG Register software

Proprietary software that interfaces with the EEG hardware for data recording and storage.

Connection schematic

A wiring diagram for the integration of an ESP32 microcontroller with a mechanical arthromotor setup is shown in Fig. 4. The main components shown include the ESP32 microcontroller, a MOSFET switch for power control, the arthromotor, and a PC connected via Serial USB.

The ESP32 microcontroller, positioned at the bottom of the diagram, serves as the central unit for receiving commands from the PC and sending control signals to the MOSFET switch, which indirectly controls the motors. It is connected to the computer via Serial USB, facilitating command reception. The computer plays a crucial role by sending these commands from the Matlab script to the ESP32 to control the arthromotor's movements and power state.

Above the ESP32 is the MOSFET switch, an essential component for security, as it activates or deactivates the power to the servo motors. The MOSFET switch connects to the ESP32 through multiple wires: Red and black wires are the power connections (VCC and GND), blue wires represent signal lines for motor control, and a green wire controls the MOSFET switch, enabling or disabling the servo power as needed.

At the top of the diagram, the mechanical arthromotor device is depicted by two motors with gear symbols, indicating the mechanical components involved. These motors connect to the MOSFET switch via power lines (red wires) and control lines (blue wires), completing the system that manages the arthromotor's precise movements based on the commands received from the ESP32.

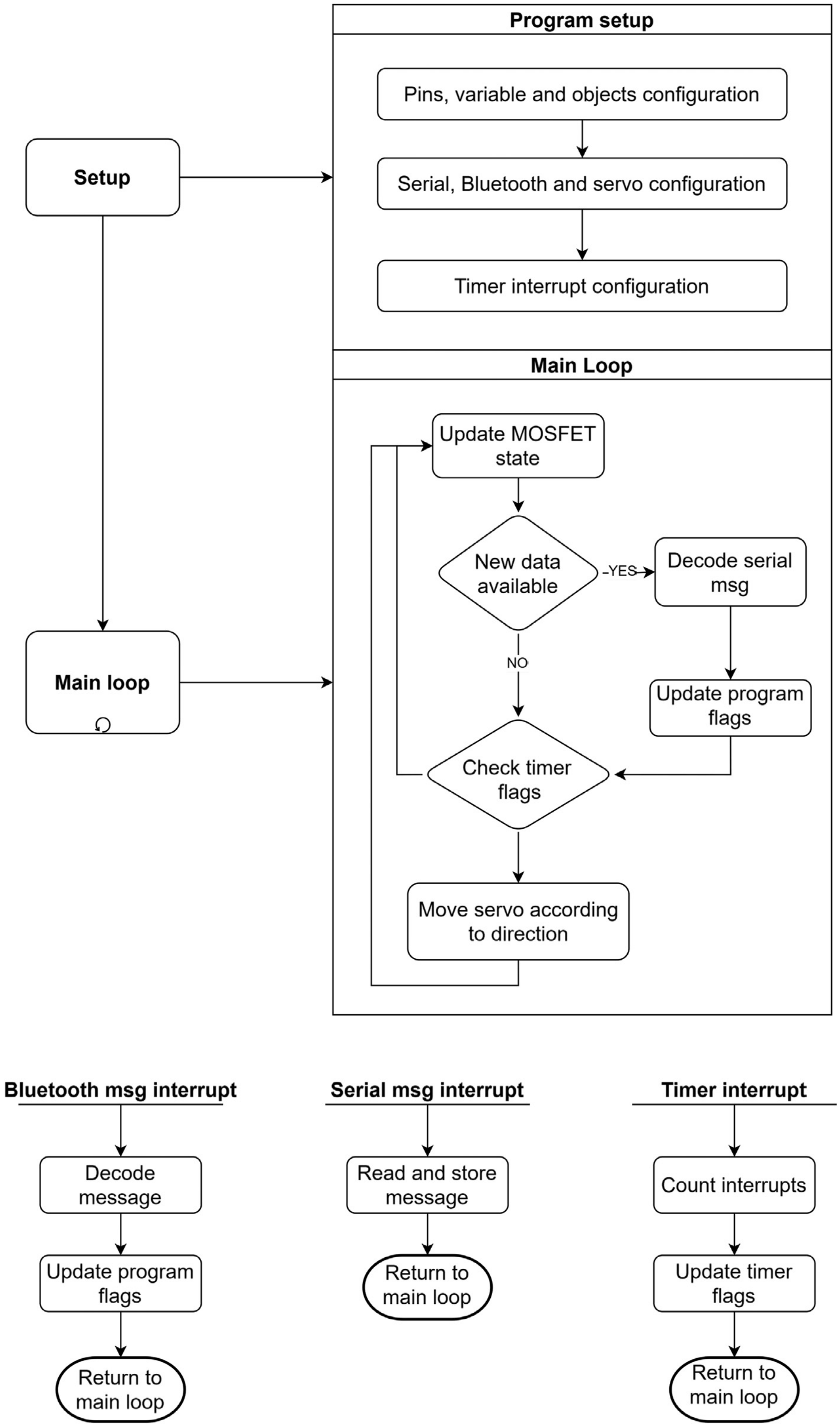

Fig. 3. ESP-32 flow chart with interrupts.

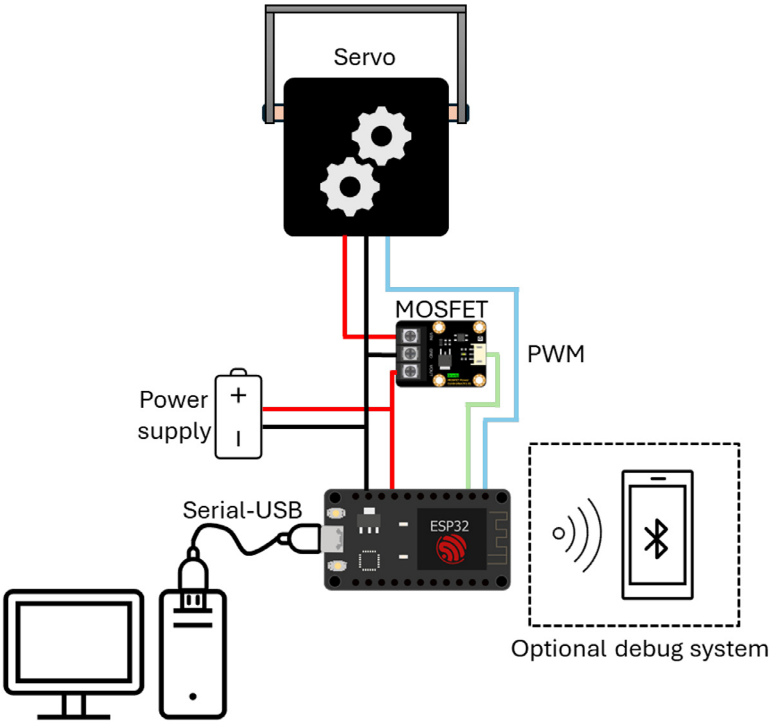

Fig. 4. Wiring diagram.

Bill of materials

To replicate this setup, the following components are required:

COMPONENT	DESCRIPTION	QTY
EEG Recording system	Cap with scalp electrodes + EEG amplifier	1
USB -Parallel port cable	Used for event marking	1
USB - MircoUSB-B	Used for serial com	1
Electrical wire	Electrical connections shown in Figure 5	-
Hex bolts M8	Mechanical connections shown in assembly	4
Bolts M3		8
Winged nuts M8		4
Hex nuts M3		8
M8 washer		4
3D Printed parts	https://github.com/FMS205/Arthromotor/tree/main/3DModels	-
RDS3115 mg Robot Digital Servo	Servomotor used for the experiment	1
Power supply 4–7 V	Instrument used for powering the Add-On	-
Gravity: MOSFET Power Controller	DFR0457	1
FireBeetle ESP32	Microcontroller used for driving the servo	1

Detailed protocol

The paradigm was tested with assessment of the modulation of proprioceptive activity by affective stimuli in children with neurodevelopmental disabilities. For this purpose, two kind of affective stimuli were used: affective visual stimuli (pleasant, unpleasant and neutral pictures) and affective tactile stimuli (affective touch, non-affective touch, no touch).

Children were in an isolated room, seating in an armchair, with their right arm resting on the armrest. Electroencephalography (EEG) was recorded from 32 scalp electrodes (ECI; Nieuwkoop, The Netherlands) placed following the international 10/20 system. Reference electrodes were placed on both mastoid bones. EEG impedances were kept below 10 kΩ. Signals were acquired by using a BrainAmp amplifier (Brain Products, Inc, Munich, Germany) with a sampling rate of 1000 Hz, a high-pass filter at 0.10 Hz, a low-pass filter at 70 Hz, and a 50 Hz notch filter.

For both affective conditions (visual and tactile), the same technical paradigm was used: touch stimuli and visual stimuli were presented in consecutive blocks grouping the same kind of affective/non-affective stimuli (i. e. affective touch, non-affective touch, pleasant pictures, neutral pictures, unpleasant pictures). Each block consisted in 15 stimuli lasting 6 s, with an interstimulus interval

Table 1
Demographic and clinical characteristics of the participants.

Participant	Condition	Age (years)	Sex	Cognitive impairment	Upper limb motor impairment	Visual impairment
ID 1	Typical development	21	Boy	No	No	No
ID 2	Cerebral palsy	16	Girl	No	Moderate	No
ID 3	Cerebral palsy	17	Boy	No	Moderate	No
ID 4	Autism spectrum disorder	17	Girl	No	No	No
ID 5	Autism spectrum disorder	16	Boy	No	No	No

of 11 s; the total duration of each block was 255 s. The task started with the display of an image on the screen, which persisted for a duration of 6 s; after 2 s, the arthromotor started the passive movement of the hand at a speed of 9°/s, and the remained in the final position (movement angle of 36°); at this moment, a picture of two hands, one with flexion and one with extension of the wrist, was displayed on the screen and the children were instructed to select and press a button to indicate the perceived position of their hand within a 5-seconds window. This was followed by a 6-second interstimulus interval presenting a white fixation cross against a black backdrop to conclude the sequence. Simultaneously, the arthrormotor returned the hand to its initial position at a speed of 15 °/s. Marks in the EEG recording allowed to offline examine the proprioception hits by comparing the position of the arthomotor and the button pressed by the children in each image.

In the visual experiment, 45 visual emotional stimuli from the International Affective Picture System were employed. Affective pictures were grouped into three categories according to valence ratings from normative data: 15 pleasant (e.g. happy faces, family or pets), 15 neutral (e.g. domestic objects), and 15 unpleasant pictures (e.g. sad and angry faces, scenes with people crying, riots, dirty environments). To ensure comparability, the positive and negative images were carefully selected to match in terms of arousal and valence intensities. Images of the same valence (positive, negative and neutral) were projected in blocks for the EEG recording.

In the tactile modality, children received manual brush strokes to the dorsal surface of their right forearm using a soft cosmetic brush (3 cm of diameter). Two lines, 9 cm apart, were demarcated on the dorsal surface of their right forearm. An auditory metronome (via headphones) guided the examiner in delivering the brush strokes in a proximal-distal direction at each of two velocities: affective touch (3 cm/s), non-affective touch (30 cm/s). For stimuli delivered at 3 cm/s the distance was covered once per 3 s (9 cm stroking area x 3 cm/s), while for stimuli delivered at 30 cm/s distance was covered 3 times per second (10 cm stroking area x 30 cm/s). Tactile stimuli begun at the same time that affective pictures, with the showing up of a fixation cross on the screen, that indicated the examiner the starting of the brushing. Brushing ended when the picture of the choosing hands appeared, equally to the visual paradigm. To match the visual paradigm, a non-touch condition was added, where no tactile stimuli was provided and the children only had the proprioceptive stimuli provided by the arthromotor.

Method validation

A pilot study for validating the method was performed in 1 youth with typical development, 2 adolescents with spastic cerebral palsy and 2 adolescents with autism spectrum disorders. Table 1 displays the demographic and clinical characteristics of the participants.

All participants could perform the tasks and participants with motor disorders had no problem to press the bottoms to choose the position of their hand.

EEG recording was segmented offline in epochs of 1200 ms duration (from −200 ms to 1000 ms relative to wrist movement onset). EEG epochs were digitally filtered (0.05 Hz low pass and 30 Hz high pass) and corrected for eye-movement artifacts by using the Gratton regression method. EEG epochs containing artifacts (maximal allowed voltage step/sampling point=100 μV, minimal allowed amplitude=−100 μV, maximal allowed amplitude=100 μV, or maximal allowed absolute difference in the epoch=100 μV) were automatically rejected. As movement was applied on the right wrist, event-related potentials of C3 were averaged within conditions and displayed in descriptive graphics. Somatosensory event-related potentials (SEP) subsequent to affective stimuli were compared to neutral stimuli. Moreover, a differentiation of SEPs for different neurodevelopmental conditions allows for the study of how different populations modulate proprioceptive processing in emotional contexts.

Fig. 5 displays two examples of these findings. The Fig. 5A displays early SEP (0–200 ms.) after affective touch (red) compared with a no-touch condition (black) in adolescents with cerebral palsy. SEP grand averages reveals a clear proprioceptive SEP curve when movement did not follow an emotional condition, whereas a less defined curve, affecting both the amplitude and latency of the SEP is seen when proprioception is processed after affective touch. The Fig. 5B displays early SEP after visualizing unpleasant pictures in typically developing (black), cerebral palsy (red) and autism spectrum disorder (blue) participants. We can observe that participants with autism spectrum disorders produce higher SEP amplitude, compared to the participant with typical development. This might indicate higher cerebral activity for processing proprioceptive stimuli when viewing unpleasant inputs, suggesting a distractor modulation of negative emotions in sensorimotor processing.

Behavioral responses further showed that participants with cerebral palsy had more errors to identify their hand position when they were exposed to affective stimuli, while emotion did not affect hits in participants with autism spectrum disorders or typical development. At Table 2 we can see that participants with cerebral palsy had lower hits than the other conditions, as expected due to their motor problems, but also, that they produced more incorrect responses in the affective conditions compared to neutral

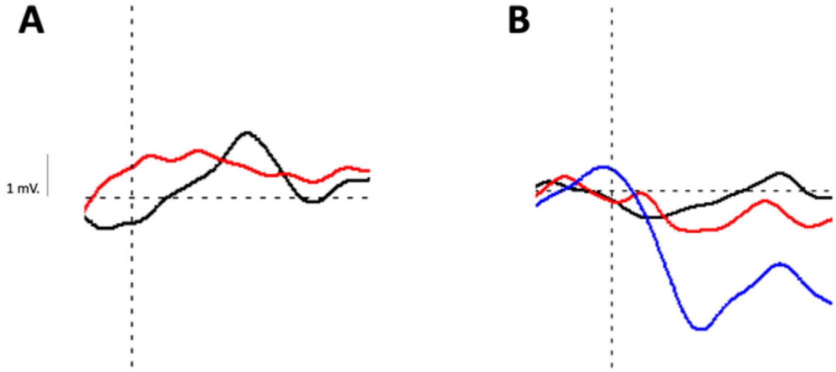

Fig. 5. Early somatosensory event potentials (SEP) showing the affective modulation of proprioceptive brain processing. A: SEP after affective touch (red) and no touch(black) in adolescents with cerebral palsy. B: SEP after visualizing unpleasant pictures in typically developing (black), cerebral palsy (red) and autism spectrum disorder (blue) participants.

Table 2
Descriptive data of proprioception hits.

Proprioception task	Pictures			Touch		
Number of hits	Pleasant	Neutral	Unpleasant	Affective touch	Non-affective	No touch
ID 1	15/15	15/15	15/15	15/15	15/15	15/15
ID 2	5/15	10/15	6/15	7/15	8/15	5/15
ID 3	8/15	9/15	8/15	4/15	10/15	5/15
ID 4	15/15	15/15	15/15	6/15	5/15	9/15
ID 5	15/15	15/15	13/15	15/15	15/15	14/15

conditions. We can also observe that children with autism spectrum disorders may have higher proprioceptive problems when exposed to another somatosensory stimuli (tactile condition) than when exposed to concomitant visual stimuli.

Although these results must be validated in bigger groups, the present findings suggest that this paradigm is a feasible and efficient way to explore the brain processing interactions between emotional and sensoriomotor inputs in populations with multiple and complex deficits.

Limitations

This method may not work in those conditions with mobility problems preventing the limb movement by the arthromotor, such as severe spasticity, anchylosis or severe deformities. Motor impairment may complicate the pressing of the buttons in the behavioral test, although time can be modified in the Matlab program to overcome difficulties due to slow movement or slow reaction time.

Ethics statements

Children and adolescents agreed to participate in the pilot study and their respective parents signed the informed consent. The study was approved by the Ethics Committee of Ethics Committee on Research from the University of the Balearic Islands (ref. 127CER19).

CRediT author statement

Francesc Mestre: Conceptualization, Methodology, Software, Resources, Visualization, Writing-Original draft. **Vicenç Canals:** Conceptualization, Software, Supervision, Resources. **Pedro Montoya**: Conceptualization, Methodology, Resources. **Inmaculada Riquelme:** Conceptualization, Methodology, Validation, Investigation, Resources, Writing- Original draft, Supervision, Project administration, Funding acquisition. **All authors:** Writing - Reviewing and Editing.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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