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Original Article

Circuit Stickers Applied to Arithmetic Teaching for People with Down Syndrome

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Abstract *- People with Down Syndrome (DS) frequently experience difficulties in acquiring mathematical concepts, which calls for teaching strategies grounded in concrete, multisensory experience. Here we develop and evaluate interactive activities built with circuit stickers for teaching basic arithmetic to people with DS. The prototype combines copper-tape circuits, tactile push buttons, light-emitting diodes (LEDs), and pre-recorded audio controlled by an Arduino Uno, and comprises three activities of increasing difficulty: banknote recognition, simple addition, and multi-item problem solving. Nine young people and adults with DS took part in individual sessions, during which attention and engagement were assessed with an observational form and with automated facial-expression analysis using the EmoLab software. The intervention was well received, and mean group attention remained at approximately 85% across all difficulty levels, whereas the need for external assistance varied between individuals and was unrelated to age. Engagement was lower and more variable than attention. Taken together, these findings indicate that combining visual, tactile, and auditory stimuli sustains concentration even as task demands increase, and suggest that circuit stickers are a promising and accessible resource for supporting arithmetic instruction for people with DS in inclusive educational settings.*

Keywords *- Circuit stickers, Down syndrome, Educational technology, Inclusive education, Multisensory learning.*

Main Conclusion *- Circuit-sticker activities combining visual, tactile, and auditory feedback sustained approximately 85% attention in people with Down syndrome across all difficulty levels, supporting their use in inclusive arithmetic teaching.*

1. Introduction

Arithmetic underpins many activities of daily living, yet people with intellectual disabilities, including those with Down syndrome (DS), often struggle to acquire mathematical concepts [1], [2]. Effective instruction for this population should therefore prioritize hands-on activities and structured routines that consolidate learning [3]. For individuals with DS, tangible interfaces and interactive circuits offer multisensory experiences that can capture attention and make abstract arithmetic content more accessible [2], [4], [5]. A representative example is MangaSticker [6], which uses circuit stickers, LEDs, buttons, and sound modules to turn illustrated stories into interactive artifacts, providing a combination of sensory stimuli that supports the learning of basic mathematical concepts [2].

The aim of this study was to develop and evaluate a circuit-sticker prototype for teaching basic arithmetic to people with DS and to examine how multisensory stimulation affects attention, engagement, and conceptual understanding. We designed interactive activities on banknote recognition and addition that use buttons, LEDs, and audio, and assessed participants' behavior through direct observation and through facial-expression analysis with the EmoLab software [7]. The intervention was well received and sustained high levels of attention regardless of task difficulty, indicating that combined multisensory stimuli foster concentration and playful involvement.

2. Materials and Methods

We conducted an experimental, descriptive, and exploratory study to evaluate an interactive circuit-sticker prototype designed to teach arithmetic to people with DS through multisensory stimulation. Behavioral data were collected during the activities with EmoLab [7], a non-invasive, computer-vision-based tool that tracks facial

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landmarks and converts micro-expressions into quantitative measures of visual attention, engagement, and emotional state.

The tool was central to this work because it allowed participants' responses to be analyzed objectively, reducing the subjectivity inherent in human observation and providing data on how multisensory stimuli influenced their interest.

2.1. Participants

Nine volunteers with DS, young people and adults aged 20 to 40 years, took part in the study. All were members of the Alfadown Project, which belongs to the Social Inclusion Reference Program (Programa de Referência em Inclusão Social, PRIS) of the Pontifical Catholic University of Goiás (PUC Goiás), Brazil. Participation was voluntary: legal guardians provided written informed consent, and participants gave their assent. The study was approved by the Research Ethics Committee of PUC Goiás (CAAE: 51159415.3.0000.0037).

2.2. Prototype Requirements

The prototype was designed to meet three sets of requirements. Functionally, each button press had to trigger the corresponding LED and audio immediately, and the activities had to be organized into three levels of difficulty. The non-functional requirements comprised visual and structural simplicity, with circuits built on paper and free of distracting elements; safety, with lightweight, non-toxic materials and no sharp edges; and brevity, with each activity lasting no more than approximately 1 min 30 s, in keeping with the participants' attention span.

The pedagogical requirements comprised multisensory stimulation through LEDs (visual), recorded audio (auditory), and buttons (tactile); an age-appropriate, non-infantilizing design, given that the participants were young people and adults; and video recording of all interactions for subsequent analysis.

2.3. Activities and Feedback Strategy

We developed nine activities, three per difficulty level, all set in the context of handling money (Figure 1). At the easy level, the participant matches a banknote to the equivalent number of R$ 1 coins; for example, given a R$ 2.00 note, the participant chooses between two coins and three coins (Figure 1a).

At the intermediate level, the participant is presented with an operation involving banknotes, such as R$ 5.00 + R$ 5.00, and selects the banknote corresponding to the result from three options (Figure 1b); one item at this level involves subtraction (R$ 10.00 − R$ 5.00). At the difficult level, the problems simulate purchases, such as working out the total cost of a R$ 10.00 sandwich and a R$ 2.00 ice pop and identifying which of three combinations of banknotes adds up to R$ 12.00 (Figure 1c).

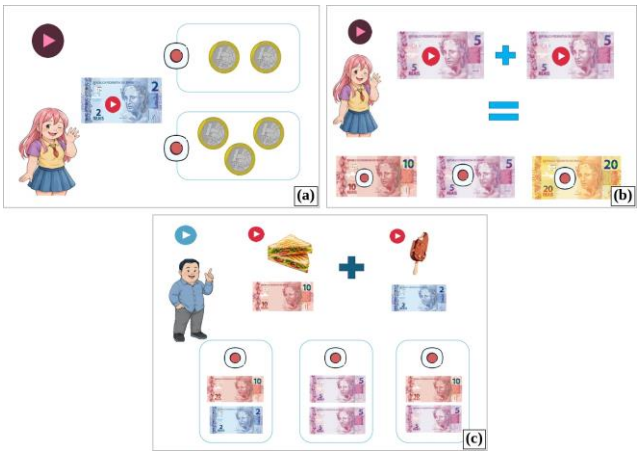


Fig. 1 Examples of the activities: (a) easy level, matching a R$ 2.00 banknote to R$ 1 coins; (b) intermediate level, adding two R$ 5.00 banknotes; (c) difficult level, calculating the total cost of a sandwich and an ice pop

Each page contains an instruction button, buttons on the banknotes and objects that announce their name or value, and buttons beneath the answer options. Selecting the correct option lights a green LED and plays the message "Congratulations! You got it right!"; selecting an incorrect option lights a red LED and plays "Aaah, not this time, but try again!", inviting another attempt.

The messages were recorded in simple, direct, and encouraging language that avoids words such as "wrong" or "incorrect", and the red LED was intended as a cue rather than a sanction. The characters were drawn with physical features of people with DS to encourage participants to identify with the material and to foster a sense of belonging.

2.4. Hardware and Materials

The prototype comprises adhesive copper tape, 4 × 4 mm Surface-Mount (SMD) tactile buttons, SMD 3528 LEDs, a DFPlayer Mini audio module, a 3 W, 4 Ω loudspeaker, and an Arduino Uno R3; their main specifications are listed in Table 1. The buttons were selected for their flat profile and the tactile feedback of their mechanical click, an important feature for users with fine motor difficulties: even beneath the printed sheet, they offer a well-defined contact area and require little actuation force. The LEDs were salvaged from a 12 V LED strip by stripping the silicone encapsulation, because their small footprint allows them to be concealed beneath the activity artwork; each LED operates at approximately 3.0–3.2 V and 15–20 mA and is driven by an Arduino digital output (5 V) through a current-limiting resistor. Instruction and feedback audio files are stored on a microSD card and played back by the DFPlayer Mini, which the Arduino controls over a serial (UART) link. The circuit is built on a 1.9 mm pressed-cardboard base (papel Paraná), and the artwork, printed on heavyweight matte coated A4 paper, is mounted over the circuit so that the circuitry remains hidden beneath the illustrations (Figure 2).

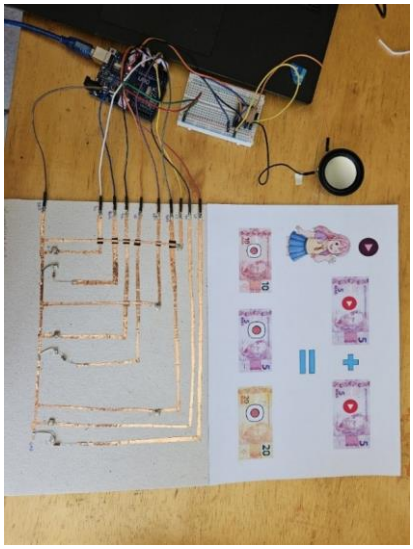


Fig. 2 Prototype of an intermediate-level activity, showing the copper-tape traces and the connections to the Arduino and the DFPlayer Mini

Table 1. Main components of the prototype and their specifications

Component	Specifications
SMD tactile button	4 × 4 × 1.5 mm; 12 V and 50 mA (max.); momentary action
SMD 3528 LED	Green and red; ~3.0–3.2 V; 15–20 mA; current-limiting resistor
Adhesive copper tape	~0.05 mm thick; conductive traces on paper
DFPlayer Mini	3.2–5.0 V; up to 100 mA; microSD (up to 32 GB); UART control
Speaker	3 W; 4 Ω; ~40 mm diameter
Arduino Uno R3	ATmega328P; 5 V via USB; 14 digital I/O pins; 32 KB flash memory
Base and print	1.9 mm pressed cardboard; 180–230 g/m² matte coated paper (A4)
Webcam	Microsoft LifeCam HD-3000; 720p; USB 2.0

2.5. Prototype Fabrication

The layout of each activity was designed in MangaSticker [6], which allows characters, banknotes, buttons, LEDs, and conductive traces to be arranged on a single page, ensuring that the physical circuit is aligned with the printed artwork (Figure 3a). Assembly comprised five steps: (i) marking the component positions on the cardboard base according to the layout; (ii) laying the traces with copper tape, with electrical tape at crossings as an additional safety measure; (iii) positioning the buttons and LEDs with tweezers and soldering them directly onto the copper tape, without drilling the base, using a magnifier stand; (iv) soldering the resistors and the jumper wires that connect the circuit to the Arduino and the DFPlayer Mini; and (v) fixing the printed sheet to the base with double-sided tape, with the buttons and LEDs aligned to the corresponding visual elements (Figure 3b). To minimize distraction, the Arduino and the breadboard carrying the DFPlayer Mini were enclosed in a small black-painted box with side openings for the wires (Figure 3c). Before the sessions, informal usability tests with adults and children assessed the size and arrangement of the buttons, the LED response, and the intelligibility of the audio; feedback was positive, and no substantial changes were required.

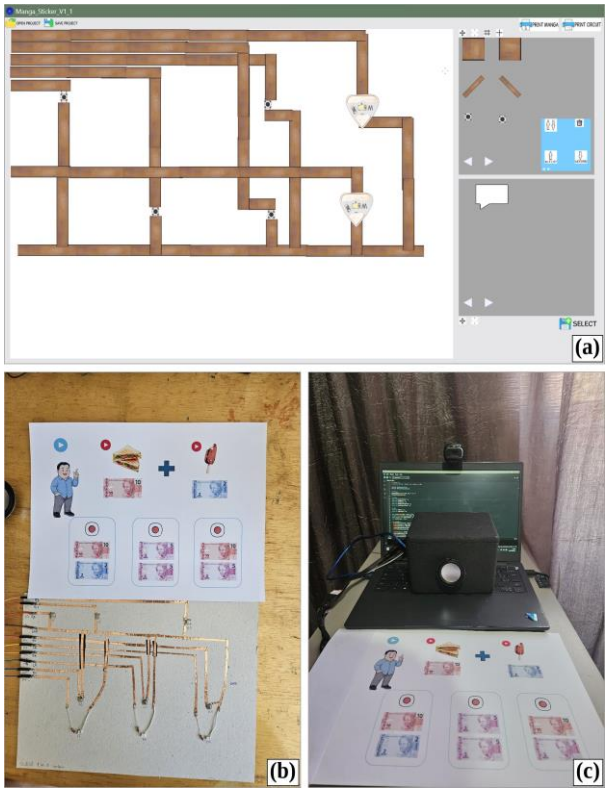


Fig. 3 Design and fabrication of the prototype: (a) layout of an easy-level activity in MangaSticker, showing traces, buttons, and LEDs; (b) printed sheet and copper-tape base of a difficult-level activity; (c) complete setup, comprising the activity, the box housing the Arduino and the DFPlayer Mini, and the laptop with the webcam

2.6. Firmware and Operating Logic

The firmware was written in C/C++ in the Arduino IDE (version 1.8.19), using the SoftwareSerial library for serial communication with the DFPlayer Mini and the DFRobotDFPlayerMini library for playback control. All activities share the same logic and differ only in the number of buttons and LEDs and in the audio files. The main function, verificarBotao(), reads the button states with software debouncing based on the millis() function, preventing spurious readings caused by mechanical contact bounce.

When a press is detected, the Arduino plays the audio assigned to that button and, for answer buttons, lights the green or red LED, which remains on while the audio plays and switches off after approximately 1.5 s (Figure 4). No fixed interaction sequence is imposed: participants may replay the instruction and the option audio as often as they wish, which promotes autonomy. The source code is publicly available [8].

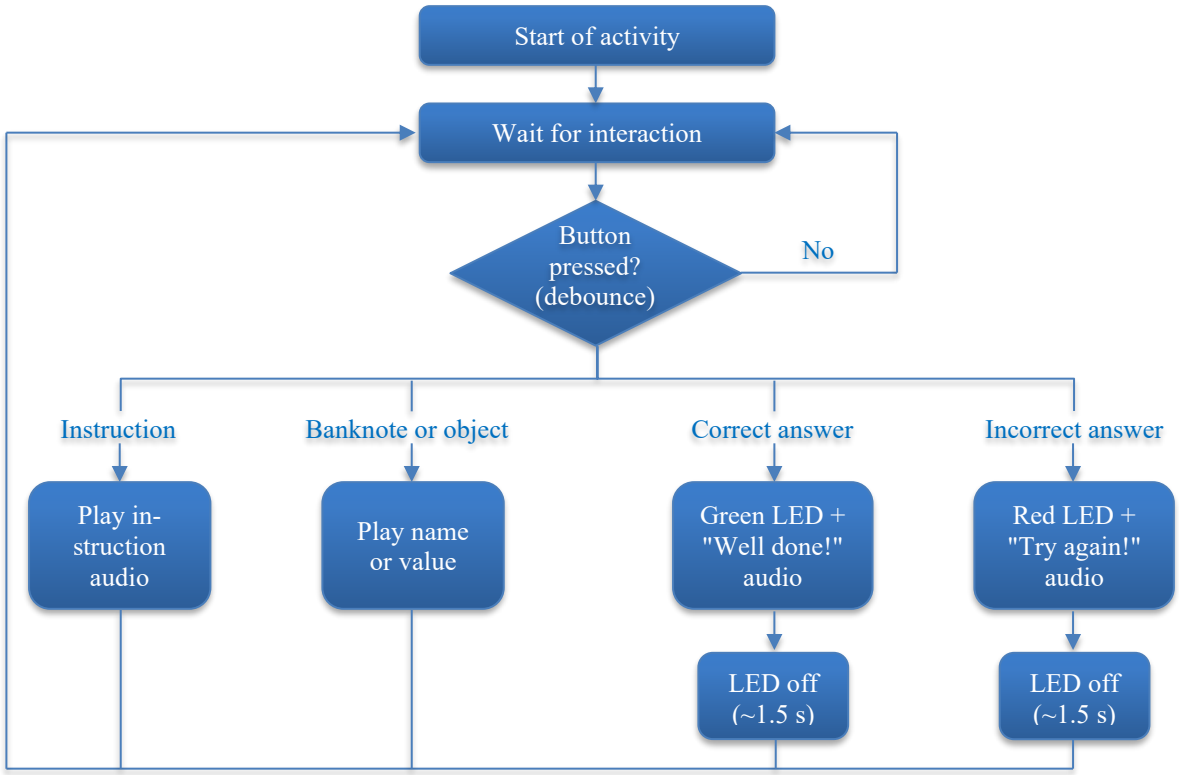


Fig. 4 Flowchart of the firmware logic used in the activities



Fig. 5 Session with one of the participants at PUC Goiás, showing the printed activity, the box housing the electronic modules, and the laptop with the webcam positioned for recording

2.7. Application Procedure

The activities were administered individually in two settings: a quiet, well-lit room at the School of Teacher Education and Humanities of PUC Goiás, and a room at the headquarters of the Down Syndrome Association of Goiás (Associação Down de Goiás, Asdown), an environment familiar to the participants, where occasional external noise occurred.

Each participant completed three activities, one per level, in order of increasing difficulty. Before each activity, the audio instructions were reinforced verbally, and participants were told that they could replay the instructions and options and try again, with no time limit.

The researcher remained beside the participant to provide operational support, explaining the buttons again when asked and changing the activity sheets. The camera was positioned unobtrusively, and specific consent was obtained for video recording and image capture. Figure 5 shows one of the sessions.

2.8. Data Collection and Analysis

Data were collected from video recordings of the interactions, which were subsequently processed with EmoLab [7]. EmoLab is an Android application, run on a computer through the BlueStacks emulator, that analyzes video frame by frame, tracks facial landmarks in regions such as the eyes, eyebrows, and mouth (Figure 6), and exports the results of each session as text files.

The video of each activity was processed in its entirety, and three indicators were extracted: attention, which estimates the degree of focus from gaze direction, head orientation, and expressions associated with concentration; engagement, which estimates active involvement in the task from micro-expressions of interest and the time spent looking at the material; and happiness, which is associated with smiling and cheek raising.

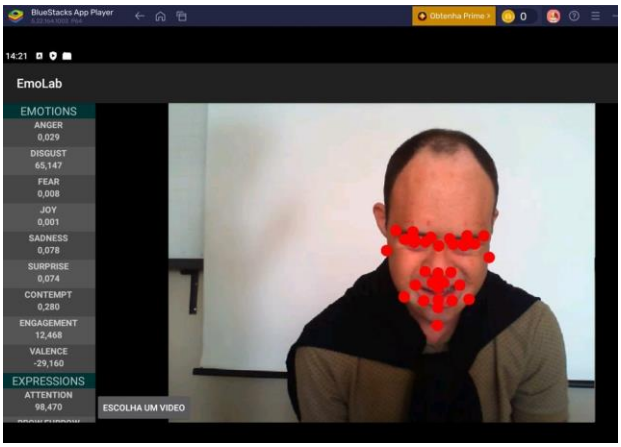


Fig. 6 EmoLab interface showing facial landmark tracking for one participant

In addition, an observational form was used to record the need for external assistance, the level of attention, the frequency of distractions, signs of frustration and impatience, and interest in repeating the activity, together with the completion time (in seconds) and the number of errors. The quantitative analysis considered correct responses, errors, completion time, and the facial indicators extracted by EmoLab, whereas the qualitative analysis drew on the behavioral observations recorded during the sessions.

3. Results and Discussion

3.1. Behavioral Observation

On the observational form, the need for external assistance was rated on a five-point scale, where 1 indicates that the participant required assistance throughout the activity and 5 that the participant completed it unaided; higher scores therefore denote greater autonomy. Scores ranged from 3 to 5 in the easy and intermediate activities and from 4 to 5 in the difficult activity, with means of 3.94, 4.33, and 4.22, respectively (Figure 7). Autonomy was lowest in the easy activity, which was always performed first, suggesting a familiarization effect: after initial exposure to the prototype, the need for assistance decreased even as difficulty increased. V09 (21 years) completed all three activities unaided, and V02 (40 years) and V05 (20 years) scored 5 in two of them, whereas V06 and V08 required more assistance only in the easy activity, and V07 in both the easy and intermediate activities. Autonomy bore no consistent relationship to age, suggesting that the need for external assistance depends more on each individual's cognitive and motor profile and on familiarity with the prototype than on chronological age.

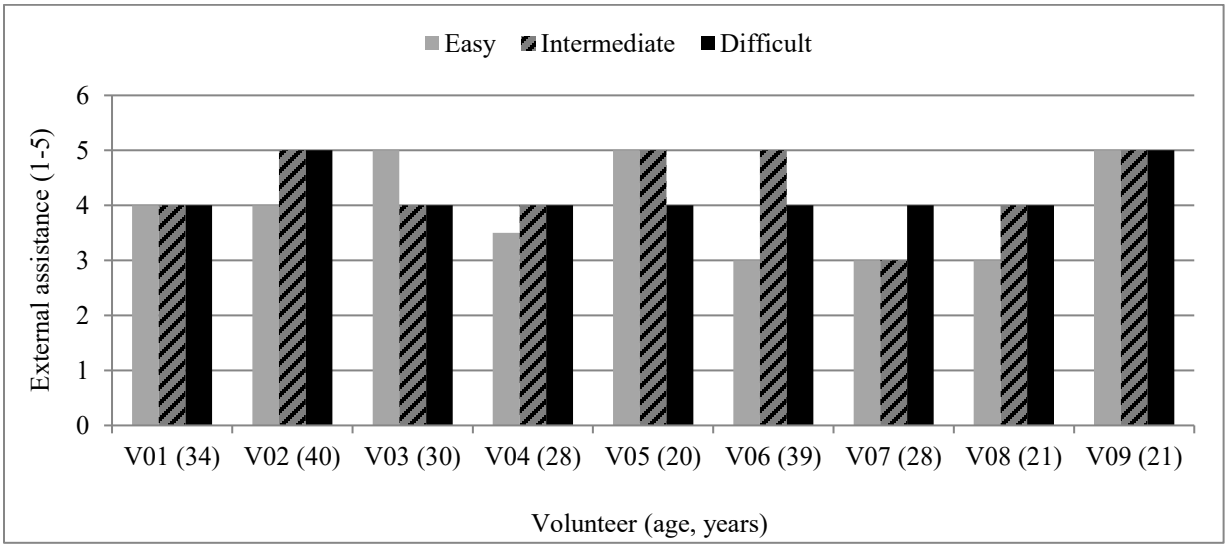


Fig. 7 Need for external assistance for each participant at the three difficulty levels, as rated on the observational form (1, assistance throughout the activity; 5, no assistance)

Evaluator-rated attention reached the maximum score (5) for all participants in the intermediate and difficult activities and for eight of the nine participants in the easy activity (V08: 4.5). All participants completed the three activities, and the records showed no notable signs of frustration or impatience as difficulty increased.

3.2. Attention and Engagement Measured by EmoLab

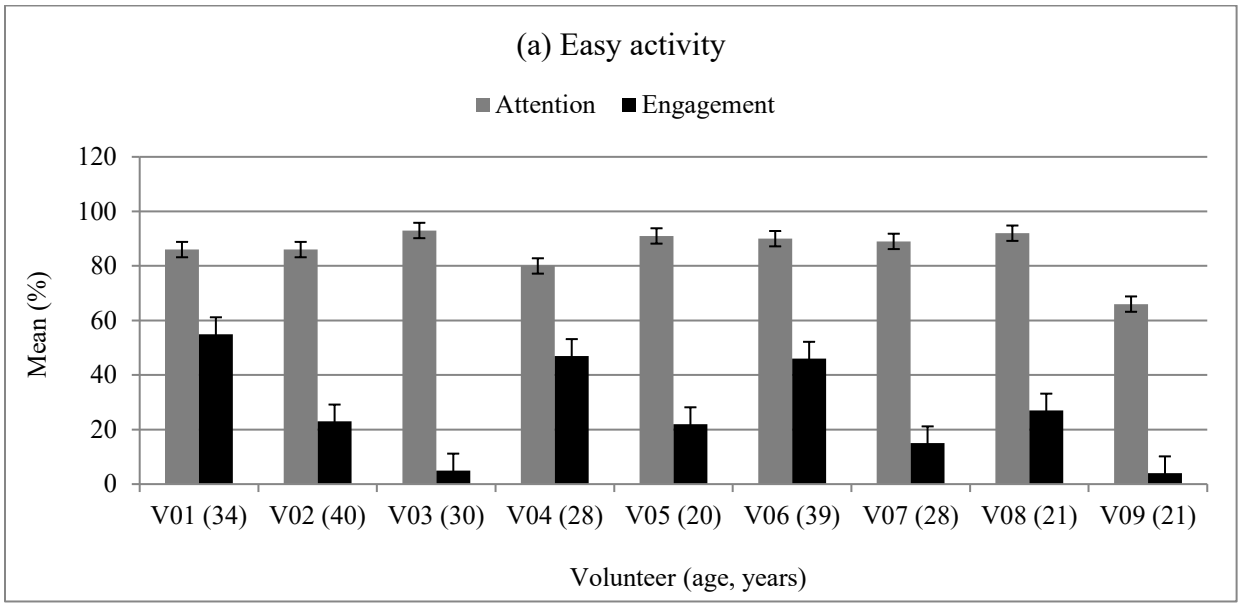
Table 2 summarizes the EmoLab indicators by difficulty level, and Figure 8 shows each participant's mean and standard deviation over the course of each activity. EmoLab could not assess V03 in the intermediate and difficult activities or V05 in the intermediate activity, because frequent facial movements prevented reliable tracking; in these cases, assessment relied on the observational form completed by the team that administered the tests. Mean group attention was 85.9%, 84.9%, and 85.9% in the easy, intermediate, and difficult activities, respectively, and thus remained stable as difficulty increased. Most participants maintained attention above 80% at every level; the lowest values were recorded for

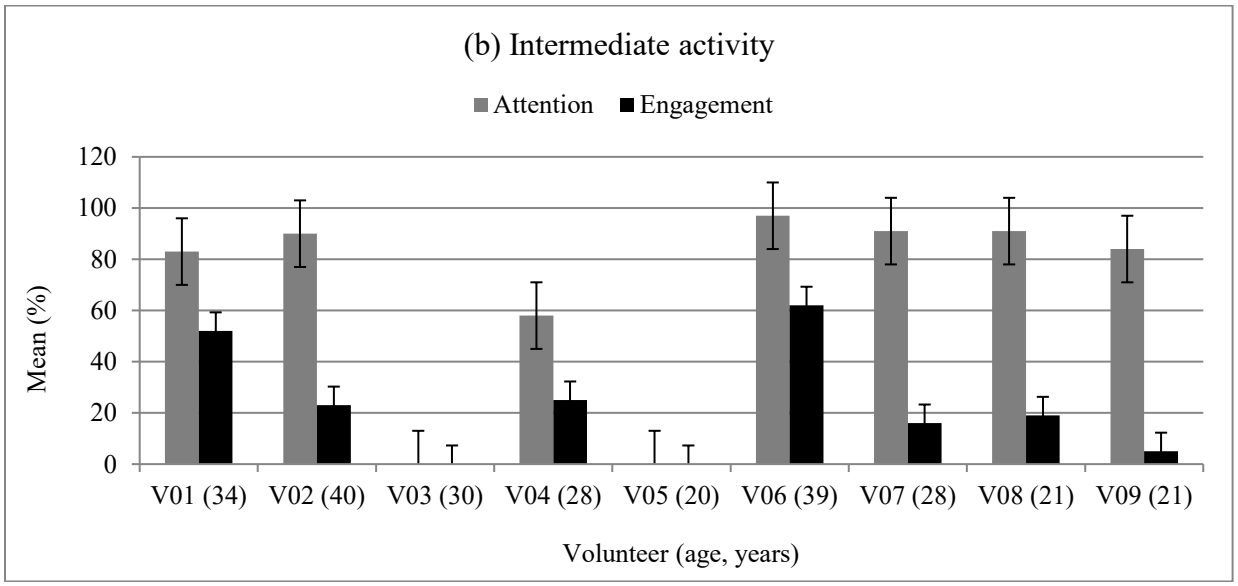
V09 in the easy activity (66.4%) and V04 in the intermediate activity (57.8%), both accompanied by high standard deviations (26.9 and 30.5 percentage points), indicative of lapses of attention interspersed with periods of focus. V06 showed the highest and most stable attention, with 97.2% and 96.2% in the intermediate and difficult activities and standard deviations of about 2 percentage points.

Table 2. EmoLab indicators by difficulty level: group mean, with the lowest and highest individual means in parentheses

Level	n	Attention (%)	Engagement (%)
Easy	9	85.9 (66.4–93.4)	27.1 (4.0–55.1)
Intermediate	7	84.9 (57.8–97.2)	29.0 (4.5–62.4)
Difficult	8	85.9 (76.3–96.2)	23.0 (5.6–59.1)

Engagement was lower and more heterogeneous than attention, with group means of 27.1%, 29.0%, and 23.0% at the easy, intermediate, and difficult levels, respectively. V06 and V01 showed the highest values (46.0–62.4% and 35.2–55.1%, respectively), whereas V03, V09, and, in the difficult activity, V05 showed engagement below 10% despite attention above 66%. Standard deviations of engagement were large, often approaching or exceeding the mean, revealing marked fluctuations within each activity. Attention and engagement therefore behaved largely independently: sustained gaze and focus on the task did not necessarily translate into facial expressions of active involvement, which points to the influence of individual factors such as interest, familiarity with the content, momentary emotional state, and each participant's characteristic facial expressiveness.





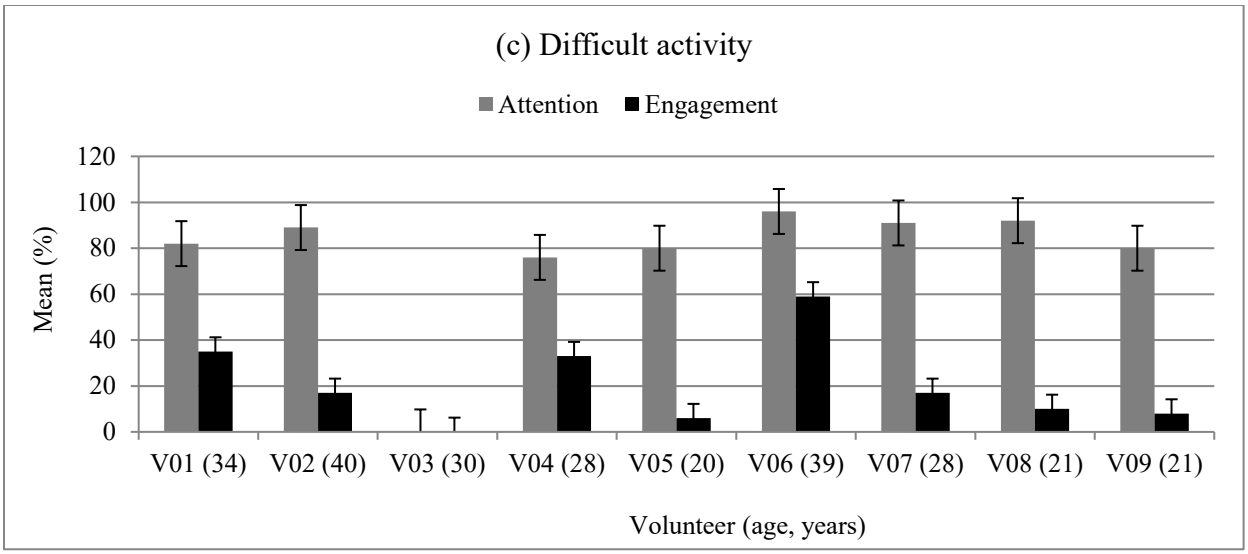


Fig. 8 Mean and standard deviation of EmoLab-measured attention and engagement for each participant in the (a) easy, (b) intermediate, and (c) difficult activities (n.d., no data)

3.3. Comparison Between Methods and Discussion

Comparison of the two methods reveals a ceiling effect in the observational ratings of attention: V09 in the easy activity and V04 in the intermediate activity received the maximum score from the evaluators, although EmoLab recorded a mean attention of only 66.4% and 57.8%, respectively. The automated analysis was thus more sensitive to fluctuations in focus during the activity, whereas human observation captured aspects such as autonomy and task completion. Likewise, age did not determine the attention measured by EmoLab, as younger and older participants alike maintained high means at all three levels (Figure 8).

The high level of attention may be attributed to the multisensory design, which combined visual, auditory, and tactile stimuli to make learning more concrete and playful. This is consistent with studies reporting the effectiveness of multisensory resources in inclusive education [2], [4], [5]. Immediate visual and auditory feedback also helped to sustain interest and allowed errors to be corrected without frustration.

4. Conclusion

Observational and automated EmoLab data indicate that the interactive activities elicited high levels of attention. Mean group attention remained at approximately 85% across the three difficulty levels (84.9–85.9%), showing that increasing complexity did not compromise focus. The need for external assistance varied between participants and decreased after the first activity, revealing a heterogeneous autonomy profile that was not determined by age. Engagement, by contrast, was lower and more variable than attention, indicating that facially expressed involvement depends on individual factors.

This study has several limitations. The small sample precludes generalization of the results; the short intervention period did not allow medium- or long-term knowledge retention to be assessed; there was no control group or comparison with conventional teaching methods; and automated EmoLab analysis was not possible in some sessions because of frequent facial movement. Future work should enlarge the sample, undertake comparative and longitudinal studies, introduce activities involving multiplication, division, and contextualized problems, and develop a stand-alone version of the prototype that requires no computer, using more compact microcontrollers and capacitive or proximity sensors.

Overall, the proposed approach shows promise for supporting arithmetic instruction for people with DS and underscores the value of accessible, interactive, and playful resources in the development of inclusive educational technologies within health informatics.

Conflicts of Interest

The authors declare no conflicts of interest.

Funding Statement

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Compliance with Ethical Standards

The study was approved by the Research Ethics Committee of the Pontifical Catholic University of Goiás (CAAE: 51159415.3.0000.0037). Written informed consent was obtained from the legal guardians of all participants, all participants gave their assent, and specific consent was obtained for video recording and image capture.

Data Availability

The prototype firmware source code is publicly available on GitHub [8]. The anonymized observational records and EmoLab outputs that support the findings of this study are

available from the corresponding author upon reasonable request. Video recordings are not shared in order to protect participant privacy.

Author Contributions

D.S.C.P.: conceptualization, methodology, prototype design and fabrication, software, data collection, formal analysis, and writing – original draft. V.A.S.: MangaSticker software, methodology, and writing – review and editing. S.S.A.: validation and writing – review and editing. T.M.G.A.B.: conceptualization, supervision, project administration, and writing – review and editing. All authors read and approved the final manuscript.

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