SPRING: Customizable, Motivation-Driven Technology for Children with Autism or Neurodevelopmental Differences

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ABSTRACT

Current research to understand and enhance the development of children with neurological differences, including Autism Spectrum Disorder (ASD), is often severely limited by small sample sizes of human-gathered data in artificially structured learning environments. SPRING: **S**mart **P**latform for **R**esearch, **I**ntervention, and **N**eurodevelopmental **G**rowth is a new hardware and software system designed to 1) automate quantitative data acquisition, 2) optimize learning progressions through customized, motivating stimuli, and 3) encourage social, cognitive, and motor development in a personalized, child-led play environment. SPRING can also be paired with sensors to probe the physiological underpinnings of motivation, engagement, and cognition.

Here, we present the design principles and methodology for SPRING, as well as two heterogeneous case studies. The first case highlights enhanced attention and accelerated skill development using SPRING, while the second pairs SPRING data with electrodermal activity measurements to identify a possible physiological signature of engagement and challenge in learning.

Author Keywords

Augmentative technology; Children; Autism; ASD; Neurodevelopmental disorders; Physiology; Motivation; Engagement; Learning; Objective outcome measures

ACM Classification Keywords

H.5.2. User Interfaces: User-Centered Design.

INTRODUCTION

Children with complex developmental needs, including many children diagnosed with Autism Spectrum Disorder (ASD), face an array of challenges in cognition, motor planning, emotion regulation, sensory modulation, communication, and social interaction [1, 10, 14]. Traditional approaches to address these difficulties, such as

Figure 1. The Smart Platform for Research, Intervention, and Neurodevelopmental Growth (SPRING) with a Shape Sorting Module.

Applied Behavior Analysis (ABA) [4] and Discrete Trial Training [18], typically present activities in a regimented learning environment, using desirable reinforcements to encourage attention and focus. Studies have shown that these frequent, discrete trialing procedures can be effective for skill acquisition, especially for children with significant delays [18]; however, these methods require a trained therapist, often for upwards of 20 hours per week [5], vary highly across therapists [19], and can limit opportunities for child-directed learning [6]. In addition, young children can be difficult to study, particularly in a quantitative manner that produces reliable and reproducible results. New technology to address these shortcomings is essential to advance research and developmental aids for these children.

This paper introduces SPRING: **S**mart **P**latform for **R**esearch, **I**ntervention, & **N**euro-developmental **G**rowth, a new hardware and software system designed to 1) automate quantitative data acquisition, 2) optimize learning progressions through customized, motivating stimuli, and 3) encourage social, cognitive, and motor development in a personalized, child-led play environment. SPRING is interdisciplinary, combining methods from psychology, mechanical and electrical engineering, computer science, education theory, and human-computer interaction.

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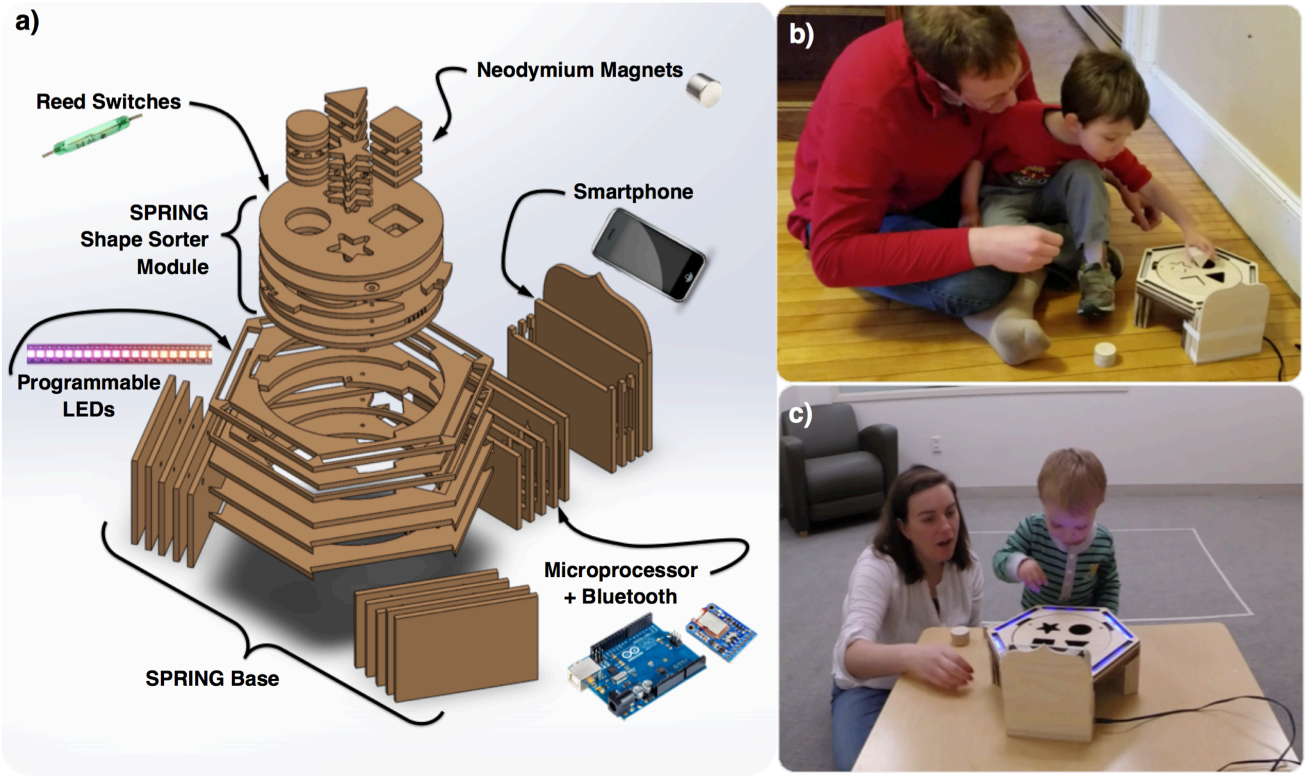

Figure 2. a) Exploded, annotated view of the first SPRING system. b) Video capture of child playing with SPRING during first user case study. c) Video capture of child playing with SPRING during pilot study, showing oscillating blue LED feedback.

SPRING is also a Tangible User Interface [20], fusing its physical-digital inputs and outputs to create new tangible technology for learning [e.g., 12, 15]. In addition, SPRING extends beyond an interactive toy platform to the research domain, enabling not only descriptive models of motivation, engagement, and neurodevelopment, but also possible *predictive* models based on fundamental principles.

In this paper, we first present the design principles of SPRING. Then, we describe SPRING's physical form, scaffolded learning characteristics, and other notable features. We then discuss how it utilizes personalized feedback to motivate learning and how this scalable customization is achieved. Next, we discuss results from two case studies, one from an early user and one from a pilot study that combines SPRING with physiological sensors. Finally, we describe limitations of the current model and improvements for the next-generation SPRING system.

DESIGN PRINCIPLES

SPRING embodies the following design principles:

Smart. Using embedded sensors, a microprocessor, and a smartphone, SPRING records time-stamped digital data and provides real-time sensory feedback in the form of LED light displays, music, videos, and other electronic stimuli (see Figures 1 and 2). These features offer a wide range of input and output stimuli to accommodate the needs, preferences, and developmental levels of each user.

Platform. SPRING is both a learning system and a research device. It supports multiple specially designed modules that can resemble toys, puzzles, or assessment tools. These Modules are designed to be removable and replaceable, allowing the activity to be adjusted to the developmental level of the child. This modularity also places most of the expensive, high-tech components in the reusable Base, making SPRING more economical.

Research. SPRING collects multimodal time-stamped data of a child's interactions during play, including the rate of play, the current activity, and the child's preferred sensory feedback. The data help *quantify* developmental trajectories for non-traditional learners, validate objective models of learning, and establish the role of motivating stimuli in children with and without ASD. We can also pair the time-synchronized data with physiological sensors to measure affective states while learning and playing.

Intervention. SPRING embodies many principles of therapy that are effective for children with ASD and other neurodevelopmental disorders [e.g., 4, 18], but it does so in a child-led, play-based environment. By automating data collection and responsive feedback, we do not require a therapist's constant presence, allowing the child to explore and learn at favorable times (even 5 am) and to pursue self-driven learning. A child's parent or therapist can build a

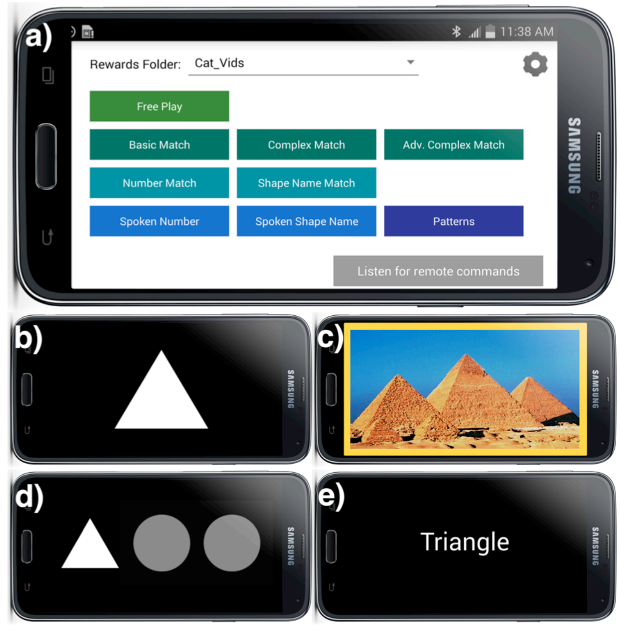

Figure 3. Screenshots of the SPRING Shape Sorter smartphone interface: a) the home screen, depicting the various scaffolded learning levels; b) a triangle prompt from the Basic Match level; c) a triangle prompt from the Complex Match level; d) a triangle-circle-circle prompt from the Patterns level, encouraging left-to-right sequential ordering; and e) a triangle prompt from the Shape Name Match level that encourages early reading skills. The dropdown menu on the home screen allows the user to select a personalized response folder matching the specific interests of the child (e.g., cat videos, rocket ships, Elmo songs). The "Listen for Remote Commands" button allows SPRING to be controlled remotely via wifi, such as by a researcher in a separate room.

personalized portfolio to match the child's current interests and can track interactions with SPRING over time (see Customization Process section).

Neurodevelopmental Growth. Fundamentally, SPRING is a learning system designed to bolster development in young children, especially those who benefit from highly personalized learning aids.

DEVICE DESCRIPTION

Base. The SPRING Base is hexagonal with a 6-inch edge length, making it 12 inches wide, tip to tip (see Figure 1). With legs situated under three of the edges, SPRING stands 6 inches high, allowing 3 inches of clearance between the Module insert and the tabletop. The Base houses an Arduino microprocessor, Bluetooth adapter, and Android smartphone, plus 108 programmable LEDs (Adafruit Neopixels) embedded along the outer edges of the Base.

Module. The SPRING Module is a circular center component that contains an activity such as shape sorting (current function), block design (in progress; see Future Work), or pretend play (planned). The Module is designed to be removable and replaceable, allowing adjustment to match the developmental level of the child.

In the current prototype's Shape Sorter Module, each shape contains a precise arrangement of neodymium magnets that trigger reed switches embedded within the layers of the Module when the shapes are inserted in their corresponding holes. Note that we have chosen the arrangement and strength of the magnets to only trigger the switches when inserted in the proper hole. These switches connect to the Arduino microcontroller in the Base, which communicates with the smartphone via Bluetooth, which then records the interaction in a data log and tells SPRING to display a personalized response.

Smartphone Interface. The smartphone runs a custom app (Figure 3) that provides prompts for activities, records inputs from the SPRING sensors, and presents dynamic, customized feedback in the form of music, videos, or images. The LEDs also provide feedback through visually engaging light displays. The phone keeps a time-stamped log file of every action – e.g., what prompt was displayed when, what sensors were triggered, what feedback was presented – allowing researchers, teachers, and caregivers to analyze the data of the user's interactions with SPRING and to time-synchronize it with other information, such as data from physiological sensors or video coding.

Scaffolded Learning

Following Vygotsky [21], SPRING Modules incorporate a scaffolded learning approach, whereby Module levels build upon one another (see Figure 3a). For example, the Shape Sorting Module begins with a free play level, where the child receives motivating feedback (e.g., lights, music, videos) for each successfully inserted shape. It then can progress to a series of matching levels, which work on matching, 2D-to-3D generalization, and abstract-to-concrete generalization. The learning continues to grow with the child, covering concepts such as sequencing, basic word and number recognition, and auditory recognition skills. Many of these concepts can be challenging to teach, so SPRING provides an opportunity for a child to repeatedly develop and hone their knowledge in a highly motivating, responsive environment.

The current prototype of the SPRING Shape Sorter Module includes the following levels:

- *Free Play:* No prompt. Shape play is reinforced with personalized feedback after each insertion.
- *Basic Match:* Screen displays a high-contrast silhouette of a shape (see Figure 3b). Child receives personalized feedback upon inserting the correct corresponding shape. Note that, if the prompt is a triangle, only placing a triangle will elicit feedback. Inserting any other shape will not produce an effect.
- *Complex Match:* Screen displays an abstract representation of a shape (e.g., a basketball, a yield sign, a starfish; see Figure 3c). As before, child receives personalized feedback only upon insertion

of the correct corresponding shape. (Feedback continues in this manner for all subsequent levels, unless otherwise specified.)

- *Advanced Complex Match:* Screen displays a more complex abstract representation of a shape or shape category (e.g., a pile of overlapping coins, a screen filled with gumballs, several boats with triangular sails).
- *Number Match:* Screen displays a number that corresponds to the number of points on a shape (e.g., '5' for the star, '4' for the square). Painting dots on each shape can assist the user. (Note: Because of the ambiguity of the circle's characteristics, this level has seen infrequent use during pilot testing.)
- *Shape Name Match:* Screen displays a word corresponding to a shape name (see Figure 3e).
- *Spoken Number:* Phone audio states a number corresponding to the number of points on a shape (e.g., "The next number is 4," for the square.) As above, this level has seen infrequent use.
- *Spoken Shape Name:* Phone audio states a shape name (e.g., "The next shape is triangle.") This level requires the user to listen closely to the prompt in order to respond.
- *Patterns:* Screen first displays a single high-contrast white-on-black shape as in the matching levels. Then, once this shape has been inserted correctly, the screen displays two shapes. The leftmost shape is white, while the other is shaded gray (see Figure 3d). Once the leftmost shape has been inserted, it turns gray and then next sequential shape becomes white. After completing the two-shape prompt, three shapes are displayed, and so on. Personalized feedback is presented only after the completion of the full sequence of shapes in each prompt. Placing an "incorrect" shape moves the user back a level within this Patterns activity (e.g., from four shapes to three) without presenting feedback.

Because language is challenging for much of our target population, SPRING does not require any verbal instructions for play; although some levels, like Spoken Name Match, work to develop receptive language. In principle, gestures, visual cues, and SPRING's feedback guide the child to advance.

Other Notable Design Features

The wooden construction of SPRING creates an aesthetic similar to classic, non-digital children's toys, placing the emphasis on a physical interaction with SPRING and the surrounding environment instead of a solely screen-based device. Children – and those with ASD, in particular – can become fixated on digital devices (e.g., tablets, phones, video games), often to the exclusion of other activities. The tangible interaction design enhances development of critical motor skills and provides tactile feedback not accessible from screen-based environments [15]. In addition, multi-player SPRING systems are in development (see Future Work) to stimulate social interaction – typically a challenging activity to motivate or teach.

Another feature is that a silicone mat – the same kind often used in baking – has been affixed to the bottom layer of the SPRING Shape Sorter Module (see blue regions in Figure 1). Diagonal slits in the silicone allow the shapes to pass through the holes with gentle pressure (comparable to the force necessary to press an elevator button). This construction serves multiple purposes: First, it ensures a more consistent response from the reed switches embedded inside the Module, which trigger more reliably with a momentary pause in the presence of the magnetic field. Second, it allows multiple shapes to remain in the Module simultaneously (see SPRING in Figure 2b), enabling more extensive opportunities for play. For example, the Module can function equally like a puzzle or a more classic through-hole sorter. Third, the mat provides proprioceptive input in the form of slight resistance. Proprioceptive feedback has been shown to have a positive, calming sensory effect for individuals, including those with ASD [8,9]. Indeed, users with and without ASD have frequently commented on this feature, stating – often with surprise – that it "feels very good" or "satisfying" to push the shapes through their holes.

PERSONALIZED MOTIVATION-DRIVEN LEARNING

In general, typically-developing children are motivated to learn and explore intrinsically, often driven by curiosity or pursuits of mastery and independence [16]. For many children with neuro-differences, however, this intrinsic motivation may be insufficient to overcome environmental distractions, sensory demands, or motor challenges required to focus or complete a task. Yet, children diagnosed with ASD or other developmental disorders often show intense, specific affinities for particular items or topics that can be leveraged to teach skills or ideas [13, 1]. Inspired by these affinities, we have designed SPRING to be easily programmable in order to provide motivating stimuli *tailored to the child*.

Note that the level of specificity SPRING provides is critical for many children with ASD. In our pilot study, we asked parents what interested their children. For neurotypical (NT) children, we were generally given broad categories of topics – cars, Legos, Star Wars, etc. – but for ASD children, the interests were much more precise:

"There are only two highly preferred videos he will attend to on YouTube…"

"He likes watching Peppa Pig… the parts where George cries…"

"He is into songs that have letters and numbers in them…"

The specific interests were also more pivotal to children with ASD compared to NT children. For example, the last mother continued:

"He is very reluctant to do anything if he is not motivated. If you hit that motivation button, you see many skills you thought he did not have."

She also mentioned that *"his reinforcers change,"* so she would let us know if there were any changes right before he came in for the study. Reinforcer variation has also been shown to improve attention and progression [7], so SPRING is rapidly and fully customizable (see Customization Process below).

SPRING also allows teachers and researchers to systematically explore methods to reduce the need for discrete reinforcement and promote intrinsically motivated exploration beyond the given task, particularly as the activities become easier or more familiar.

Customization Process

SPRING is designed to be customizable across three important domains: 1) the activity, 2) the developmental level of the activity, and 3) the feedback.

Activity. The play facilitator (e.g., a teacher, therapist, or caregiver) can change an activity by removing SPRING's central Module and replacing it with a new Module. The current prototype houses a Shape Sorting Module; however, new Modules with different activities are nearing completion (see Future Works), allowing the facilitator to select the most developmentally appropriate activity for the user on that day or play session. The Module twists in and out of the Base like a large screw, making it easy to exchange in a matter of seconds.

Activity Level. As described previously, a facilitator can choose among scaffolded learning activities with a Module. These levels are designed to developmentally build upon one another in order to achieve the "just right" challenge or place the user in the zone of proximal development [17, 21]. While these levels are currently pre-programmed into the smartphone interface, they could be open-sourced to allow individuals to create their own "just right" levels for any Module. (While we intend to open-source this design for broad use, this feature is not currently supported.)

Feedback. SPRING is also customizable in its feedback, producing lights, music, images, or videos of nearly any topic or theme. The programmable LEDs built into the SPRING Base can produce an extensive array of visual displays, from slow glowing lavender lights to multicolor rainbow patters to bright red lights that bounce around like ping pong balls. We have programmed over 25 light shows into the microcontroller and created a Settings screen on the SPRING app that allows the play facilitator to select which light displays to include as feedback options (see Figure 4). This interface allows the facilitator to choose light displays that match the preferences and regulatory needs of the user. For example, if the user finds diffuse glowing lights calming and regulating, they can be selected to the exclusion of other options. Likewise, if lights are aversive

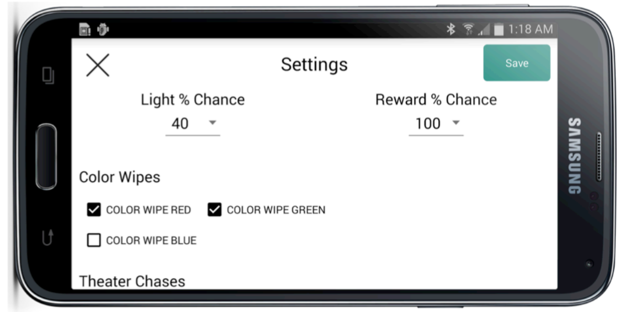

Figure 4. Settings screen of the SPRING smartphone interface. The user can select which LED light shows will appear (check marks) and how often they will be cycled through the reward feedback (40% of the time here). The "Reward % Chance" drop down option allows the user to set the feedback to appear less than 100% of the time, which can be useful when a child is proficient at the skill and does not require consistent, immediate feedback.

stimuli, all options can be deselected. To date, most users prefer the widest range of options and feedback novelty.

The likelihood of seeing LED feedback is also customizable using the drop-down option at the top of the Settings screen (see Figure 4, "Light % Chance"). Choosing 100% will present only LED feedback while 0% will display no LED feedback. Most users seem to prefer pseudo-random lights to appear as feedback about 40% of the time, but this percentage has been set across the full range of options to meet the needs of users during our early testing.

In addition to LED feedback, SPRING can present almost any multimedia file that can be played on a smartphone. Video clips, images, and audio files can be downloaded from the internet or from the user's personal directories and then loaded into a personalized folder on the SPRING smartphone microSD card. Currently, SPRING contains over 2000 "pre-loaded" multimedia references in 50+ categories, ranging from cat videos to pinwheels to princesses. These clips are stored in folders on the phone microSD card and can be accessed via the drop-down menu on the SPRING app home screen (see "Rewards Folder" at top of Figure 3a). A user can also build a personalized folder by copying files into a new folder on the microSD card. As soon as the app is reopened, the new, personalized "reward folder" will appear in the drop-down menu of the home screen. This procedure requires time to source the desired videos, images, or audio files initially, but once the material is saved, the customization process takes less than a minute. Additionally, the folder-based drop-down menu allows a teacher or caregiver to switch between different feedback schemes for different users – or the same user with varying regulatory needs or desires for that day – in a matter of seconds.

In early pilot testing, this feature has proven critical in addressing the user preferences as he or she interacts with SPRING. Some children with ASD love a topic so acutely that still images and short, 3-5 second video chips are the

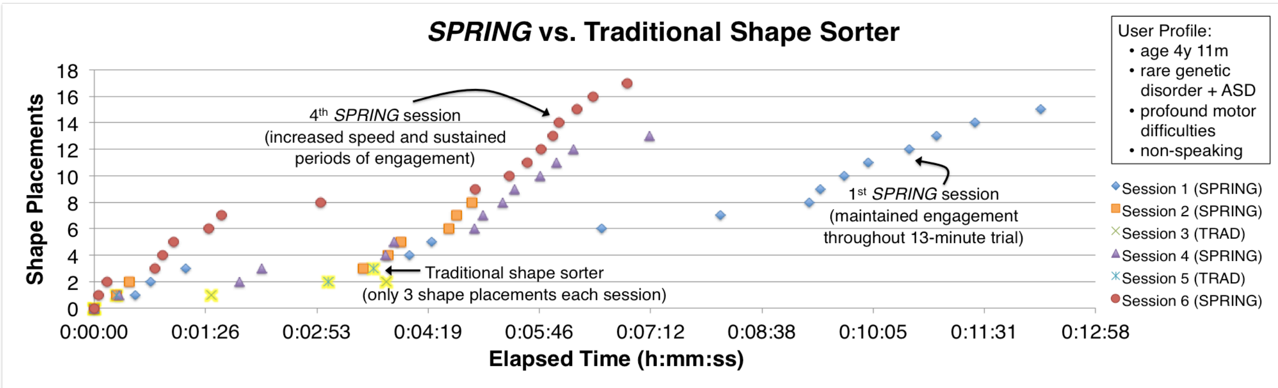

Figure 5. Plot of cumulative shape placements as a function of time for a single user over 6 sessions within an 8-day period. Sessions 1, 2, 4, and 6 used the SPRING Shape Sorter Module while Sessions 3 and 5 used a traditional, non-responsive shape sorter. Each session with a traditional shape sorter resulted in only 3 shape placements. Note the sustained periods of engagement with SPRING and the increasing rate of shape placement with subsequent SPRING sessions. Parental guidance and praise was similar across all trials.

"just right" motivating response. For other children, however, particularly those for whom the activity is a marked developmental challenge, anything less than a 15-second clip of a highly preferred song or scene appears to elicit visible frustration or agitation. These experiences – and their corresponding physiological measurements – are still being collected and analyzed and will be presented in a future paper.

PRELIMINARY RESULTS & DISCUSSION

Case 1: Motivation-driven learning for child with autism

Figure 5 presents the first multi-day case study with SPRING. The user was an almost-5-year-old boy, diagnosed with autism as well as a rare genetic disorder that involves significant difficulties in motor planning (e.g., he was still an early walker and did not use his hands for the first few years of life). As such, shape sorting was still an arduous and ambitious task, demanding his full attention, both cognitively and physically. He could not speak and did not respond to spoken words, though he was highly motivated by "dancing" light shows and musical feedback.

Over the span of eight days, the child played with either SPRING or an off-the-shelf, non-digital Fisher Price shape sorter in his home in a Floortime-style [22] play environment with at least one parent (see Figure 2b). Various LED shows were chosen as reinforcements, and no settings were changed between sessions. Each session was video recorded, and consent/assent was obtained from the parents and child prior to the start of the study.

Note that Figure 5 depicts only complete shape placements. It does not capture incomplete attempts (close to the correct hole, but not all the way in) or incorrect attempts (e.g., placing the triangle sideways in the square hole). Since these attempts are valuable – and often clever – steps in the learning process, modifications to capture them are underway (see Future Work).

During the first session (Figure 5, blue diamond markers), the child and his mother were seated on the floor in front of SPRING. Initially, the child tried to twist away from his mother, but his mother quickly placed a circle in SPRING, causing a red strip of light to race around the Base. As soon as he saw the lights, the child turned himself toward SPRING and calmly watched the light show without moving. He then reached for a shape – independently and without prompting – and attempted to place it in the circle hole. He was unsuccessful, appeared frustrated quickly, and tried to twist away again. With prompting from his mother, he attempted four more shape placements (unsuccessfully) before successfully placing a circle (Figure 5, 00:32). Then, unprompted and unaided, he almost immediately inserted the circle again (00:44). He then tried to place the square in the circle hole. With help from his mother, he was able to place the square in its proper hole (01:11) before needing a short break.

After a few minutes, the child returned to SPRING with his father but did not try any shape sorting until he saw the lights again. Then, with noticeable concentration and only minor assistance, he inserted the circle twice (04:05, 04:22). The child then began to move about the room and chose to place shapes in SPRING intermittently over the next few minutes. Then, for the last four minutes of the session (09:00-13:00), the child played intently and consistently, placing eight shapes without complaint or breaks. He was outwardly regulated and visibly engaged in the task+lights.

The following day (Session 2, orange square markers), the child approached SPRING without complaint and independently inserted the circle twice without prompting or assistance. He then attempted to insert several shapes with no assistance for over a minute (not captured in Figure 5 data), but after failing to elicit any light shows, he walked away. With prompting, he returned to SPRING and independently inserted six pieces. Then the child became fixated on the camera being used to film the session and did not reengage with SPRING.

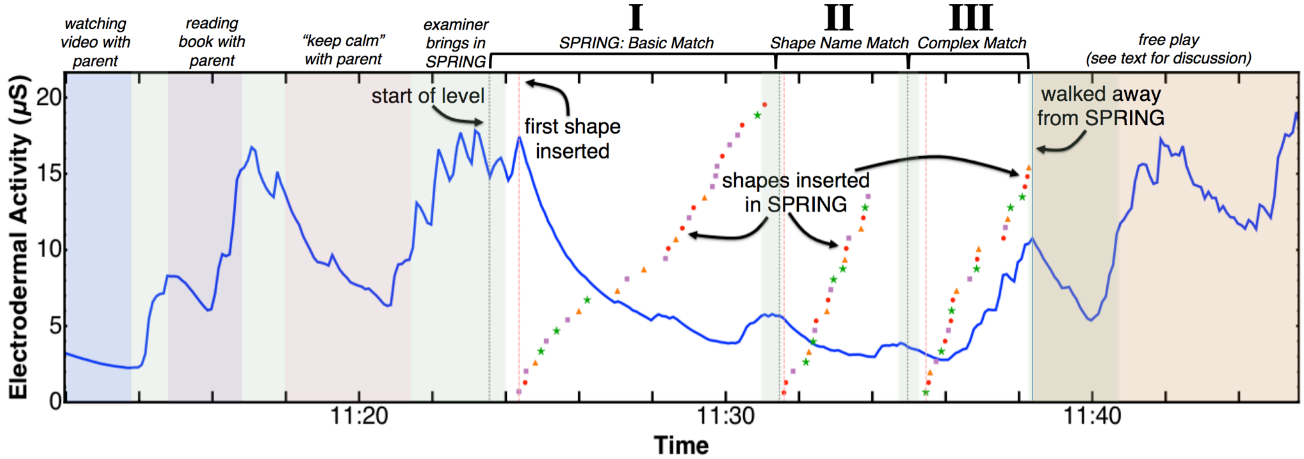

Figure 6. Plot of a child's electrodermal activity (EDA; blue line) as a function of time during a pilot case study with time-synchronized SPRING data overlaid. EDA data were captured via a wrist-worn sensor with wet electrodes at 32 samples per second. These data were filtered by taking a moving median of +/- 3 seconds about each point (i.e., 192 samples per window). Vertical gray dotted lines indicate the start of a new level using the SPRING Shape Sorter Module, while vertical pink dashed lines mark the child's first shape placement for that level. Each colored shape marker denotes placement of that shape in SPRING. Video capture shows that the declines in arousal correspond to the child's deep engagement or boredom in relatively rote activities that were either visibly easy (I; Basic Match) or too challenging (II; Shape Name Match). However, during the last level (III; Complex Match), the child's arousal rose as he strategized the correct shape. These data suggest that SPRING may facilitate measurement of physiological signatures of learning and engagement for children.

The first session with a traditional shape sorter (Session 3, green 'x' markers) was completed on an indoor platform swing in an effort to help regulate and engage the child. The child had not been exposed to a traditional shape sorter in the previous 12 months. With hand-over-hand assistance and extensive prompting, the child was able to insert three shapes. (These placements were manually timed and counted using the video.) The child did not attempt any shape placements without prompting. After four minutes, the child was markedly agitated and repeated attempts to reengage or redirect the child to the activity were unsuccessful, so the session was ended.

In order to determine if the child's agitation was related to the unresponsive shape sorting activity or to something else, the child was offered SPRING less than two minutes after the end of the previous session (Session 4, purple triangle markers). He then calmly and steadily played with SPRING for the next eight minutes. Almost any gap in placements during Session 4 were moments when the child was *attempting* to place the shape. The child remained visibly engaged and outwardly regulated the entire session.

The next session (two days later) with the traditional shape sorter (Session 5, brown 'x' markers) went similarly to Session 3 with three shape placements over seven minutes, each with extensive assistance and prompting. The child again became agitated and repeatedly tried to leave the activity. The father tried singing songs and tickling the child to help calm him and reinterest him in the shapes without success. The session was then ended.

The final session with SPRING (Session 6, red circle markers) began with the child independently inserting seven shapes in under two minutes. After a brief distraction, the child was easily directed back to the toy (without complaint) and proceeded to insert another nine shapes in less than two minutes.

These data show a clear improvement in shape placement and engagement over time, but only with the motivating sensory feedback via SPRING. This result suggests that the feedback was a *necessary* feature for the child to learn and progress in this activity. In addition, it indicates that standard methods to evaluate this child's skills in shape sorting, which typically do not involve responsive feedback, might underestimate his ability and potential.

Case 2: SPRING + physiological sensors

The second case study is part of a larger pilot study with SPRING. Over a dozen children, age 2-5, both with and without ASD have participated, with another 18 planned. As the study is ongoing and the data are heterogeneous, a full description of the methods, results, and analysis will be discussed in a subsequent paper. In Figure 6, we present a single child's data, showing the ability of SPRING to time-synchronize quantitative measures of learning with physiological data and to deliver new insights into engagement, challenge, and motivation.

The child (male, age 2) and his mother were recruited from the Boston metro area and participated in the study in a clinical room at a local university (see Figure 2c). After providing informed consent, the child, parent, and examiner each wore a wireless heart rate monitor with chest electrodes (Actiwave Cardio) and a wireless electrodermal activity (EDA) and accelerometry sensor with wet wrist electrodes (Affectiva Q Sensor) to record their physiology. The study was video and audio recorded.

After watching a video (Figure 6, blue shaded region), reading a book (purple region), and trying to "keep calm" (pink region), all with his mother, the child was introduced to SPRING. (Green shaded regions indicate the examiner's presence in the room.) According to parental report, the child did not have strong affinities for any one topic, but did enjoy "cars, trucks and construction vehicles." The SPRING reward folder was set to a collection of vehicle images, gifs, and short (3-5 second) video clips with sound; 40% of the time, an LED light show would appear instead of a reward on the screen for variety [7].

The SPRING activity level during Stage I (Basic Match; see Figure 3b) was developmentally appropriate and appeared to be relatively easy for the child. He first appeared motivated by the novelty and general shape sorting feature of SPRING, but when he realized – through verbal prompting from his mother (*"Look! It asked for a square and you put in a square and you got a truck!"*) – that placing the shape corresponding to the image on the screen produced an image of a type of vehicle he enjoyed, he appeared to become more deliberate about his shape placements, responding directly to the screen prompts in order to see more vehicles. During this time, the child's EDA steadily declined (Figure 6, blue line, ~11:24-11:30), suggesting calm engagement in a rote activity or potential boredom [3, 10]. Towards the end of Stage I, the child began to rouse himself by shouting out the names of the shapes and prompts (*"Square!" "Car!"*) and bouncing in place while playing. The EDA in Figure 6 reflects these attempts to increase his own arousal with a small rise around 11:30:30.

Given the child's success with basic matching, the next level was set to Shape Name Match (Figure 6, Stage II), where a shape word on the screen prompts the user to insert the corresponding shape (see Figure 3e). This level was developmentally advanced for a two year old, but we were investigating whether the child would be motivated to work out what the words meant in order to continue seeing cars and trucks. Yet, without maximal assistance from his mother, the level was too difficult and the child began playing his own "game" with the shapes – placing all four shapes in SPRING and then pushing them all through the holes. (The silicone mat supports the shapes before they are pushed through the holes.) This approach had the inadvertent effect of producing the desired feedback once out of every four shape placements (since, after inserting all four shapes, one of them would match the word on the screen). Since inserting shapes appeared to be easy for the child, he was effectively doing a much simpler activity than the word reading. His EDA levels continued to decline during this stage, again suggesting rote engagement or possible boredom (Figure 6, blue line, ~11:31:30-11:34) [3, 10].

In Stage III, the child began playing the Complex Match level (see Figure 3c). At first, the child continued playing his newly invented game of placing all four shapes, but then, with prompting from his mother (e.g., *"Look! It's a waffle! What shape is the waffle?"*), he began to reengage with perceived excitement in the moderately challenging learning activity. His EDA rose markedly during this activity (11:36:00-11:38:20), suggesting that the child had entered a zone of proximal development or encountered a "just right" challenge [17, 21]. These data may indicate a possible *physiological signature of engagement and learning*; however, follow-up studies are necessary to more systematically probe this physiological state.

Immediately following his last shape placement, the child was invited to free play with age-appropriate non-digital toys (blocks, trucks, baby dolls, etc.) in the center of the room, away from SPRING. His EDA immediately fell (11:38:28), reaffirming his engagement in the previous moderately challenging activity. After a minute and a half (11:40:00), his EDA rose as he became physically active with the toys (knocking down block towers, carrying boxes across the room, etc.). These results are consistent with previous studies of physiology and child activity [10, 3].

FUTURE WORK

A number of discrete improvements to address limitations of the current design are in progress:

Mapping pre-learning and exploratory strategies

In the current SPRING Shape Sorter Module, binary reed switches detect and timestamp the placement of shapes, limiting our information about the learning strategies or exploratory methods used *before* the shape was inserted. For example, did the child try to place the star in the circle hole before successfully placing it in the star hole? Or did s/he attempt the star hole immediately – indicating cognitive awareness of the shape correspondence – but lacked the motor prowess to ultimately place the star through the hole?

By replacing the reed switches with analog voltage Hall effect sensors, we will be able to track the unique magnetic signature of each shape while it is still on the *surface* of SPRING. Additionally, a piezoelectric microphone situated just below the surface of the Module provides a clear indicator of any movement of the wooden shapes against the wooden surface. These modifications are currently underway.

Proximity detection

By adding a close-range (10-80 cm) proximity detector, we will be able to record when a child approaches SPRING and pair that information with the speed with which s/he engages. For example, if a child approaches but does not engage, it may indicate that the task is too challenging or the feedback is not enticing enough. This modification is in progress.

Linked, "social" SPRING

Eliciting social interactions such as joint attention, turn taking, and cooperative play can be especially challenging for children with ASD, and making SPRING more socially integrated is the most common request we have received regarding the platform. Social skills are difficult to teach and are even harder to objectively assess [e.g., 1]. In response, we are designing and building a linked, multi-user SPRING system that wirelessly pairs multiple SPRING devices. Their smartphones communicate in real-time over an open chat room, providing simultaneous data-logging and feedback from all devices. Then SPRING can provide personalized, motivating feedback after players have collaborated on a playful request. SPRING can scaffold, cueing users to take turns or work cooperatively during SPRING levels.

For example, consider a new Shape Sorter Module with four different shapes (e.g., crescent, heart, cross, hexagon). If a prompt from the SPRING smartphone interface requests a heart, only the player with a heart can elicit the feedback, necessitating cooperation and/or social exchanges between players. Likewise, a teacher or caregiver could do the prompting, further extending the social dynamic. Similar modes of cooperative play have been envisioned for other SPRING Modules within a linked, "multi-player" setting.

New modules

We also have designed Modules that inspire ring stacking (similar to Towers of Hanoi), pretend play (e.g., making meals or shopping), and language skills (e.g., prepositions and spatial relations). Every Module employs the same Base and the same motivation-driven principles discussed earlier in the paper.

Block design module

The next Module for SPRING (in progress) detects the placement and orientation of nine cubes. Similar to the WAIS Block Design cubes (see Figure 7), the blocks have two solid red sides, two solid white sides, and two red/white sides split diagonally. This design allows the user to engage in creative, open-ended play by forming pictures and patterns or more structured play through design prompts. At the same time, by mimicking the WAIS blocks, we are able to compare SPRING data to decades of neuropsychological research. These data may further contribute to building and assessing computational models of cognition, motivation, and problem solving.

Objective outcome measures

A primary motivation to create WAIS-like blocks for the next Module is to explore using SPRING as a TUI neuropsychological assessment tool. Current assessment or outcome measures often lack reproducible objectivity or fail to capture the true potential of non-standard users (e.g., the first case study user whose performance with a classic shape sorter was markedly lower than that with SPRING). Hence, we aim to develop a system that is reliable, reproducible, sensitive to small or subtle changes, and able to detect changes over time (i.e., longitudinal improvement or plateauing). In addition, by making it highly motivating and play-based, we hope that it is easy to administer repeatedly, and fun and engaging for our target population.

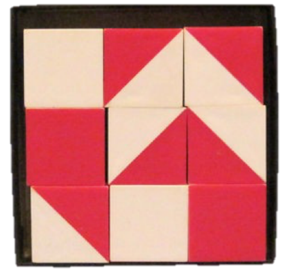

Figure 7. Wechsler Adult Intelligence Scale (WAIS) Block Design cubes. Each cube has two sides of solid red, solid white, and half red-half white. The next SPRING Module will create a TUI version of this classic activity.

CONCLUSIONS

We have introduced SPRING: a tangible, customizable, responsive device designed to accelerate learning and skill acquisition for children with neurodevelopmental differences. The design approach and inspiration for SPRING stem from its governing principles of self-motivated, child-led play, but SPRING also records objective data, rendering it a novel scalable system for systematic, long-term studies of motivation and learning behaviors. Two early case studies using the SPRING Shape Sorting Module illustrate SPRING's ability to accelerate development through motivating feedback and provide possible quantifiable physiological signatures of proximal development and engagement. With its extensible modules, personalized motivating feedback, and behavioral data logging, SPRING is well-positioned to provide data-driven insights to advance learning and development for all children.

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