DataSpoon: Overcoming Design Challenges in Tangible and Embedded Assistive Technologies

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ABSTRACT

The design of tangible and embedded assistive technologies poses unique challenges. We describe the challenges we encountered during the design of "DataSpoon", explain how we overcame them, and suggest design guidelines. DataSpoon is an instrumented spoon that monitors movement kinematics during self-feeding. Children with motor disorders often encounter difficulty mastering self-feeding. In order to treat them effectively, professional caregivers need to assess their movement kinematics. Currently, assessment is performed through observations and questionnaires. DataSpoon adds sensor-based data to this process. A validation study showed that data obtained from DataSpoon and from a 6-camera 3D motion capture system were similar. Our experience yielded three design guidelines: needs of both caregivers and children should be considered; distractions to direct caregiver-child interaction should be minimized; familiar-looking devices may alleviate concerns associated with unfamiliar technology.

Author Keywords

Assistive technology; cerebral palsy; kinematics; eating.

ACM Classification Keywords

K.4.2. [Computers and Society]: Social Issues – *Assistive technologies for persons with disability*.

INTRODUCTION

"One of the greatest challenges is quantifying children's abilities; putting them on some sort of scale that would enable me to see how they're doing relative to the general population, as well as their progress relative to themselves" (Occupational therapist, 13 years of experience).

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Figure 1. DataSpoon, a sensor-based spoon that seamlessly assesses the self-feeding skills of children with cerebral palsy.

Eating is a complex process with physiological, biomechanical, and behavioral aspects involving the entire body [15]. Disruption in eating may lead to malnutrition, poor growth, developmental delay and loss of general health and well-being [1]. Typically developing children gradually shift to higher levels of independent eating, usually mastering self-feeding by the age of three years [9,15,19]. In contrast, children with motor disorders such as cerebral palsy (CP) often have significant difficulties mastering self-feeding [5,20]. CP describes a group of developmental disorders of movement and posture leading to activity restriction that is attributed to disturbances occurring in the fetal or infant brain [18]. Motor impairment may be accompanied by a seizure disorder and by disturbances of sensation, cognition, communication and behavior [2].

To date, little data exist concerning the biomechanics of grasping utensils or food and bringing it to the mouth, control over the activity kinematics and kinetics, and issues related to motor planning and learning among children with CP. Tangible user interfaces have the potential to record such data, thereby providing caregivers with valuable assessment information about each child. As illustrated by the quote at the beginning of this paper, quantitative assessment data may greatly assist professional caregivers, and potentially lead to more effective treatment of self-feeding difficulties.

We set out to assess the self-feeding skills of children with CP via a novel instrumented spoon that monitors movement kinematics involved in self-feeding. The spoon, called

DataSpoon (previously SenSpoon), was designed using rapid prototyping in an iterative process of consultations with professional caregivers and safety experts.

In this paper we discuss the unique challenges of designing an instrumented spoon for children with CP, describe how we overcame these challenges in our design (see Figure 1), and report findings from a study validating the DataSpoon against a "gold-standard" system for assessing 3D kinematics. The lessons learned during this process could assist researchers and designers in future endeavors to develop instrumented utensils or tools.

RELATED WORK

Food-related interactions have been recognized as a challenge for the HCI community because physical, physiological, and social factors have to be taken into account [6]. It is particularly challenging to design such interactions for young children, and even more so for children with disabilities, due to developmental and safety concerns. Examples of food-related interactions include interactive food trays, bottles, and eating utensils.

Food Trays

Playful Tray [14] aims to reduce meal completion time with a weight-sensitive tray that tracks children's eating actions. These are then used as input for an interactive game embedded within the tray. ExciteTray [7] is a digital food tray that rewards self-feeding with visual feedback in the form of a colorful light display. Its goal is to motivate young children throughout the gradual process of acquiring independent eating skills.

Bottles and Cups

Playful Bottle [4] is an augmented water bottle that uses a smartphone to track water intake. It aims to encourage drinking by using water intake as input for a mobile game. FunRasa [16] is an interactive drinking platform that expands the drinking experience by electrically stimulating the user's tongue as well as superimposing virtual color onto the drink.

Eating Utensils

EducaTableware [12] are interactive tableware devices intended to make eating more enjoyable by emitting sounds when a child eats or drinks. Sensing Fork [10,11] is a fork-type sensing device that detects children's eating actions and chosen food items. This device is connected to a smartphone that analyzes sensor data, and provides feedback through a game application. Interactive training chopsticks [3] are used as controllers for an augmented mirror application game. The goal is to help children develop the skill of eating with chopsticks. Taste+ [17] aims to enhance the flavor of food, as well as restore taste to those who have lost it. Sour, bitter and salty tastes can be generated by pressing a button on the handle of a spoon. HAPIfork [8] is an electronic fork that tracks eating speed. It vibrates when the user eats too fast, thereby promoting slower and healthier eating. Liftware [13] is a stabilizing handle designed to counteract hand tremor during eating. The device detects tremors, and automatically moves in the opposite direction in order to stabilize the utensil.

While these systems address various challenges experienced while eating and drinking, they have not been adapted to the unique requirements of children with CP, nor have they sufficiently focused on the requirements of professional caregivers. DataSpoon thus extends prior work by focusing on the needs of professional caregivers, assisting them by quantitatively assessing the self-feeding skills of children with CP. Furthermore, DataSpoon analyzes complex data from movement kinematics.

DESIGN REQUIREMENTS

DataSpoon was designed in an iterative process, consisting of consultations with professional caregivers, a safety expert, and rapid prototyping. Our main challenge was balancing between three types of requirements: user requirements, technical requirements, and safety requirements.

User Requirements

DataSpoon has two types of users – children with CP who grip the spoon in their hand and use it for self-feeding, and professional caregivers who use the data derived from the spoon, along with their existing expertise, to assess children's self-feeding skills. Hence, our first step was identifying the unique requirements of both children and caregivers. Based on prior work by Zuckerman et al. [21], who interviewed professional caregivers (occupational therapists, physiotherapists), the following requirements were identified:

Physical requirements: The spoon should be comfortable for a child to grip, and as similar as possible to standard spoons with regard to its physical dimensions (weight, handle length and width, handle texture, bowl size, bowl angle) to ensure ecological and social validity. The handle should be round, made out of plastic or silicone. In addition, the spoon should be easy to clean.

Assessment requirements: The spoon should enable caregivers to quantitatively assess the self-feeding skills of each child during routine meals, eliminating the need to schedule a special assessment session. The following variables should be recorded and/or calculated: smoothness and accuracy of movement, grip force, trajectory from the plate to the mouth, speed of movement, duration of meal, and amount of food consumed. Most caregivers envision the output of the spoon as a series of graphs, facilitating comparison of the child's motion kinematics to normative data. These graphs should be simple and easy to comprehend, providing caregivers with a quick overview or snapshot of the child's skill level, as well as the ability to review more detailed data when required. Associated metrics summarizing the main outcomes are also important.

General requirements: The spoon should not interfere with natural face-to-face interaction between the child and the caregiver.

Technical Requirements

In order to meet the users' requirements, the spoon should contain sensors to detect movement kinematics during self-feeding, classify the data into clear and meaningful categories, and visualize the data in real-time on another device accessible to the caregiver. It should also enable a more in-depth analysis of the data at a later time. In addition, electronic components must be small and light-weight, because an overly cumbersome spoon would be unusable.

In order to measure all variables specified by caregivers, the spoon would have to contain multiple sensors. Each additional sensor would result in a bigger and heavier spoon. Therefore, at this stage in development, we limited the number of sensors incorporated in the spoon, focusing on kinematic data from an accelerometer and gyroscope, which provide a rich data set. Additional sensors (e.g., providing kinetic data) will be incorporated in future versions.

Safety Requirements

To ensure DataSpoon is safe to use, we consulted the director of the bio-medical engineering department at a major medical center. He is responsible for overseeing all equipment safety. He specified the following requirements: the spoon should be battery-operated and not require high-voltage electricity; all electronics should be covered, preventing any direct contact between the electronic parts and the child or moist food; all surface materials should be non-toxic; data transmission should be wireless to prevent tangling of cords while eating.

DESIGN PROCESS

To find the right balance between all design requirements, we iterated on several form factors using 3D printed models.

Physical Design

In our initial models, both the spoon's bowl and handle were 3D printed, with all electronic components embedded within the handle (see Figure 2, top). However, to increase safety, we decided that the bowl should be made of a more durable material, suitable for multiple eating and cleaning sessions. Hence, we settled on a physical design that includes two main components: a metal spoon bowl taken from a standard ("off-the-shelf") spoon, and a 3D printed plastic handle, printed with EOS PA 2201 – a bio compatible material approved for contact with food. The handle was designed to tightly hold the spoon bowl with all electronic components securely embedded within it. The handle was divided into two compartments. The sensing and communication board was placed closer to the bowl and covered with liquid silicone to ensure fluid-resistance. The 3xCR2032 coin cell batteries and switch unit were placed in a second compartment towards the base of the handle. This compartment was designed to be easily accessible by removing its cover, enabling swift replacement of batteries by the caregiver (see Figure 2, bottom). Coin cell batteries were selected for their thin profile, and because our safety expert advised against lithium ion batteries.

Figure 2. Various form factors considered (and eventually rejected) during the iterative design process of DataSpoon.

Technical Design

DataSpoon was implemented using the IMUduino BTLE board (http://www.femtoduino.com/spex/imuduino-btle) for movement sensing and Bluetooth communication. IMUduino is a 40x16mm Arduino clone, weighs 2.7 grams, with a 9/10 DoM/DoF motion and orientation sensor leveraging the on-board 3-axis gyroscope, 3-axis accelerometer, and 3-axis digital compass. The board also contains a Nordic nRF8001 Bluetooth Low Energy chip, which we paired wirelessly with an Android smartphone to classify and visualize data in real-time or for later analysis.

Safety Approval

We presented the working prototype to the safety expert, who tested it, including submerging it in a glass of water. He approved DataSpoon as a safe device to use with the target population for research purposes.

Movement Detection – Initial Classifier

We started with a simple classifier to distinguish between high magnitude-level and normal magnitude-level of self-feeding movement patterns. The classifier was written in

Java and runs on Android. The accelerometer and gyroscope data are transmitted to a smartphone and include the acceleration XYZ, pitch, yaw, and roll. At rest, the acceleration magnitude level equals 1g. Initial data collection and analysis showed clear differences between typical eating behavior and non-typical eating behavior. The maximal acceleration magnitude level of typical self-feeding reached 1.2g, whereas the acceleration magnitude level of non-typical self-feeding reached 1.4g and even 1.6g at times. Based on this initial data, we created a classifier with a simple cut-off acceleration magnitude at 1.4g, and tested it as a visualization aid, highlighting certain areas on the output graph as high-energy movement vs. low-energy movement (see Figure 3). This simple classification was a first step; we then followed up with a formal validation.

Figure 3. Data is streamed from the spoon to an Android smartphone in real-time via Bluetooth. It is then classified and presented to the caregiver in a graph.

VALIDATING DATASPOON

In order to validate DataSpoon, we compared data recorded by the spoon to kinematic data obtained from a 6-camera motion capture system called "Qualisys" (http://www.qualisys.com). Qualisys (QL) data were collected at 100 Hz. Two healthy female participants (both right handed, aged 35 and 24 years) performed natural eating movements from an imagined plate to mouth and back to a point on the table (see Figure 4). Movements were performed at three speeds (self-selected slow, comfortable, fast), and from three positions of the table start position to the mouth. Three movements were collected for each speed and location. Spoon data (accelerometers, gyroscope) were collected simultaneously.

QL data were processed using QTM (Qualisys AB) and Matlab. Gaps in marker data were spline-filled and rigid body rotations of the spoon were computed. Movement onset times were manually detected based on visual examination of gyroscope data (timings were not compared between systems as the setup was not time-synchronized). Spoon data were interpolated to 100Hz (spline

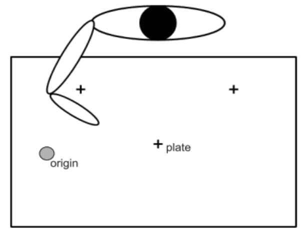

Figure 4. Experimental setup for the validation study. Participants sat in front of a table and made natural eating movement with their right hand starting from an origin point on the table, via an imagined plate in one of three locations on the table, to mouth and back to the origin point.

interpolation, Matlab). One file was excluded from the analysis due to technical issues with the measurement.

Three phases were defined in the eating cycle: (1) Dip: the spoon moves to the plate and picks up food, (2) Transport: the spoon moves from the plate to mouth, and (3) Lowering: the spoon moves from mouth back to the point of origin. Events in the eating cycle were automatically detected using pitch, roll and yaw data from the spoon. The onset of the transport phase (end of dip phase) was defined as the first positive peak in roll signal after a negative peak (see Figure 5), whereas the spoon "in mouth" event (end of the transport phase, beginning of lowering phase) was detected with the absolute peak in yaw signal. The yaw direction was defined with respect to an arbitrary "zero". However, we believe that it is the change over time of yaw which is relevant in order to detect eating cycle events (specifically spoon in mouth). Thus, a change in yaw direction implies to a change in eating phase.

Intraclass correlation coefficients (two-way mixed model, ICC(3,2)) were computed for several outcome variables in the dataset which were defined as functionally relevant: duration of the three movement stages (dip, transport, lowering) indicating the ability to transition between movement phases, range of roll in the dip phase, indicating affordances of the scooping movement), and standard deviation of roll and pitch in the transport phase (indicating stability of transport to mouth). Results are described in Table 1 ($p < 0.05$ for all variables). ICC values were fair to good (0.4-0.75) for one variable (standard deviation of pitch), and excellent (> 0.75) for the other six variables.

While only two participants participated in the validation study, each participant performed movement in three different directions, three different speeds and three repetitions of each condition. Thus, we believe that we have obtained variable movement kinematics from different ecologically-valid movements to support our validation. Since Qualisys and DataSpoon data were collected from the same movements, a small sample size may be sufficient. In the future, we plan to perform a full-scale validation study with children, both typically-developing and with CP.

Domain	Variable	Qualisys (Mean ± SD)	DataSpoon (Mean ± SD)	ICC	95% CI
Phase transitions	Dip duration (s)	1.68 ± 0.78	1.66 ± 0.74	0.99	[0.97 0.99]
	Transport duration (s)	1.07 ± 0.96	1.11 ± 1.05	0.99	[0.98 0.99]
	Lowering duration (s)	2.13 ± 1.21	2.12 ± 1.15	0.99	[0.98 0.99]
Scooping range	Pitch range – dip (deg)	62.70 ± 19.22	32.67 ± 12.55	0.90	[0.73 0.97]
	Roll range – dip (deg)	58.79 ± 14.47	67.28 ± 7.45	0.79	[0.39 0.93]
Stability	SD pitch – transport (deg)	2.72 ± 1.09	3.02 ± 1.17	0.59	[-1.6 0.86]
	SD roll –transport (deg)	8.55 ± 3.20	8.38 ± 3.11	0.77	[0.33 0.92]

Table 1. Means, standard deviations and Intraclass correlation coefficients for outcome variables derived from DataSpoon and from Qualisys, a 6-camera motion capture system.

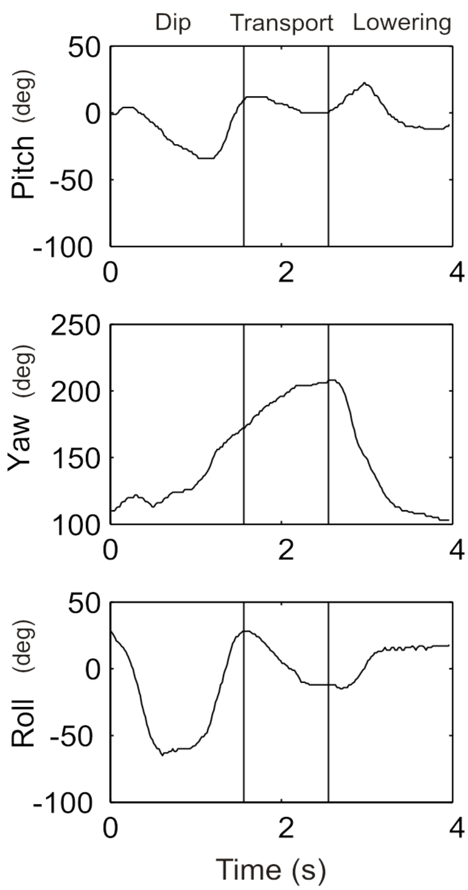

Figure 5. Example output of pitch, roll and yaw angles from a movement at comfortable speed. Vertical lines mark automatically-detected transitions between phases of the eating cycle.

EVALUATION WITH CAREGIVERS

We presented the DataSpoon prototype to professional caregivers, and asked them to evaluate it. We did not include children in the current stage since it was important that experts approve the spoon design before involving either typically developing children or those with CP.

Participants

Four professional caregivers, each with 12 to 21 years of experience, were recruited through professional acquaintance with a member of the research team. All participants regularly assess motor skills of children with disabilities.

Method

Participants were invited to participate in a group discussion on assessing children's self-feeding skills using a novel instrumented spoon. The session lasted approximately two hours. First, participants filled out a questionnaire regarding their professional experience and current use of assistive technologies. Then, each participant used DataSpoon to measure their own movement kinematics. They were asked to rate the spoon on two 5-point Likert scales: how comfortable was the spoon to grip, and how clinically relevant were the variables measured by the spoon. Lastly, participants watched two video clips depicting self-feeding, one of a person with CP and one of a typically developing person. Participants were asked to write a short description of the depicted self-feeding sessions. They were then presented with a visualization of each session, created by DataSpoon, and asked whether the quantified data could assist them with their assessment. The entire meeting was audio recorded with participants' consent. Recordings were later transcribed and independently analyzed by two researchers to identify emerging common themes.

Results

Participants described several advantages and disadvantages of assistive technologies. Advantages include quantitative data that are accurate and can be compared, based on the specific skills of each individual child. These types of data may assist with devising treatment plans and tracking progress, as well as potentially improving communication with parents and other caregivers. Disadvantages include the required effort to learn a new tool and persuade others to use it, especially those who are not technologically savvy. Furthermore, there were some concerns that it may detract from the caregiver-client interaction. Currently, most participants do not use assistive technologies for assessment purposes.

Ratings of DataSpoon are presented in Table 2. Overall, it was rated highly, with a mean score of 4.0 for grip, and 4.3 for relevancy of measured variables (out of a maximum 5). The caregivers suggested that a shorter spoon with a rounder handle would be easier to grip. Most would also like to measure grip force. They agreed that the weight of the spoon was acceptable.

Participants found it difficult to understand the data visualization in its current form, and were not sure how it corresponded with feeding difficulties portrayed in the presented video clips. Thus, although they reported that DataSpoon measures clinically relevant variables, the data should be visualized in a more intuitive manner.

ID	How comfortable is the spoon to grip?	How relevant are the measured variables?
1	4	–
2	4	4
3	5	5
4	3	4
Mean ± SD	**4.0 ± 0.82**	**4.3 ± 0.58**

Table 2. Ratings (1-5) of DataSpoon by professional caregivers, after using it to measure their own movement kinematics.

Clearly, the results of this evaluation are limited because they did not involve children, only feedback from professional caregivers. Despite this limitation, the evaluation validated the relevancy of the measured variables, and provided useful information regarding required changes in the design.

FINAL DESIGN OF DATASPOON

Based on the feedback of professional caregivers, we re-designed the handle of the spoon, making it shorter and rounder (see Figure 6), thus easier to grip.

To do so, we explored the constraints engendered by battery choice and on/off switch placement. We began with 3xCR2032 coin cell batteries, but switched to 4xLR44 button cells for the smaller radius that allowed a rounder handle. We also iterated on several switch locations. We started with an internally located switch, which enabled protection from moist food as well as accidental switching off by the child. However, this location forced the caregiver to open the spoon in order to switch it on or off, making it difficult to use. On the other hand, an external location leaves the switch unprotected from moist food and from accidental switching off by the child. Moreover, it could negatively influence the child's grip.

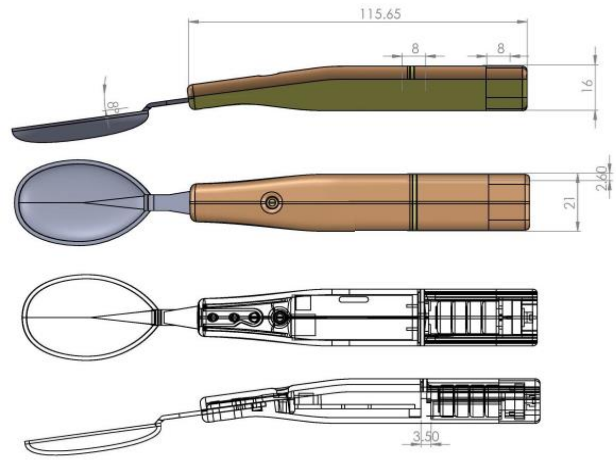

Figure 6. Following feedback from professional caregivers, the spoon handle was re-designed, to be shorter and rounder.

In the final iteration, an external switch was placed at the base of the handle in a recessed notch to prevent inadvertent switching off (see Figure 7). The final design is presented in Figure 1.

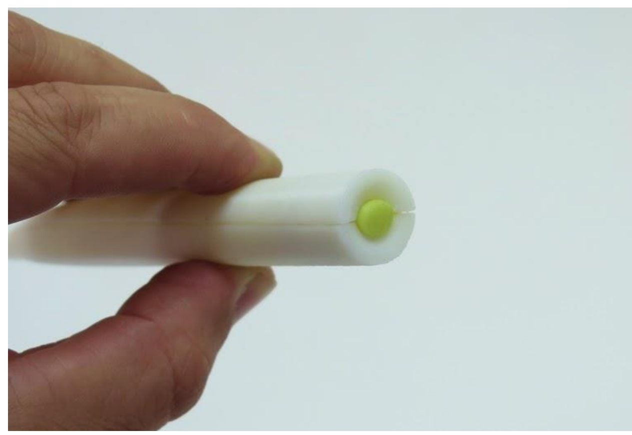

Figure 7. An external switch was placed at the base of the handle in a recessed notch.

DISCUSSION

Designing assistive technologies tailored to the unique needs of both children with disabilities and their caregivers is challenging, especially with regard to eating-related technologies. It requires constant balancing between potentially contradictory user requirements, technical requirements, and safety requirements.

The introduction of a novel assistive technology presents advantages and disadvantages alike, for both children and caregivers. Designers must keep both user groups in mind, and address the advantages and disadvantages for each group. In the case of DataSpoon, the advantages for caregivers include quantitative data regarding the self-feeding skills of each child, which may augment existing assessment practices. The advantages for children include integration of assessment into daily routines, relinquishing the need for special assessment sessions. Disadvantages for both caregivers and children include the required effort to learn how to use a new technology, and a potential distraction from caregiver-child face-to-face interaction. In order to minimize the disadvantages, we strived to design DataSpoon to be as authentic as possible to standard spoons with regard to its physical dimensions. In addition, we kept all electronic components hidden by embedding them inside the handle. This made the spoon appear less intimidating, and also safer to use. In addition, we leveraged the ubiquitous adoption of smartphones in everyday life, and used the smartphone as both the computation unit and the data visualization unit. While DataSpoon transmits data in real-time, files are also stored locally on the mobile device, enabling caregivers to remain fully focused on the child during meals, and only examine the data at a later time. We thus strived to augment natural interaction between caregiver and child, not replace it.

Future work will include data collection through the spoon with typically developing children, in order to establish normative baseline regarding the movement kinematics involved in self-feeding. Then, we will collect data with children with CP, and compare their performance to the norm, as requested by professional caregivers. In addition, we will simplify the spoon's visualization of motion kinematics data. These achievements will turn DataSpoon into a viable assessment tool for professional caregivers, helping them devise treatment plans tailored to the individual needs of each child. Eventually, we aim to connect DataSpoon to additional tangible interfaces or visualization devices, for example a digital food tray similar to the one described in [7]. This will enable DataSpoon to provide real-time feedback to the child as well as the caregiver, opening the door to utilizing DataSpoon for treatment, and not only assessment.

CONCLUSION

In this paper we presented the design, implementation and validation of DataSpoon – an instrumented spoon that monitors movement kinematics during self-feeding, and helps professional caregiver assess the self-feeding skills of children with CP. DataSpoon was designed using rapid prototyping in an iterative process of consultations with professional caregivers and safety experts. Our final design strives to reach an optimal balance between user requirements, technical requirements, and safety requirements.

Based on the lessons learned during the design process, we advise designers of assistive technology for children with disabilities to follow three main guidelines: (1) The needs of both caregivers and children must be taken into account. Moreover, since safety regulations may prevent designers from evaluating preliminary designs with disabled children, caregivers may serve as the best alternative, and provide valuable feedback at early stages of the design process. (2) Direct interaction between the caregiver and child must not be compromised, because it is fundamental for successful assessment and treatment. Assistive technologies should strive to augment face-to-face interaction, not replace it. (3) Assistive technologies should preferably resemble tools and artifacts already familiar to caregivers. Familiarity may reduce concerns regarding the required effort to learn and use a new technology, and as a result increase adoption and use by caregivers.

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