Wearable Assistive Technologies for Autism: Opportunities and Challenges

Esma Mansouri Benssassi
School of Computer Science, University of St Andrews, UK
Juan-Carlos Gomez
School of Psychology and Neuroscience, University of St Andrews, UK
LouAnne E. Boyd and Gillian R. Hayes
School of Information and Computer Sciences, University of California Irvine, USA
Juan Ye
School of Computer Science, University of St Andrews, UK
E-mail: juan.ye@st-andrews.ac.uk

Abstract

Autism is a lifelong developmental condition that affects how people perceive the world and interact with others. Challenges with typical social engagement, common in the autism experience, can have a significant negative impact on the quality of life of individuals and families living with autism. Recent advances in sensing, intelligent, and interactive technologies can enable new forms of assistive and augmentative technologies to support social interactions. However, researchers have not yet demonstrated effectiveness of these technologies in long-term real-world use. This paper presents an overview of social and sensory challenges of autism, which offer great opportunities and challenges for the design and development of assistive technologies. We review the existing work on developing wearable technologies for autism particularly to assist social interactions, analyse their potential and limitations, and discuss future research directions.

1 Introduction

Autism, a lifelong neurodevelopmental condition often referenced more broadly as Autism Spectrum Disorder (ASD), includes a large spectrum of various developmental conditions. People with an autism diagnosis frequently report or exhibit challenges in typical socialisation and communication. These challenges can have a significant negative impact on autistic people[1]'s social life, their opportunities in education and employment, and their quality of life in general. Rises in the global prevalence of autism are well-documented [11] and present new challenges for the future of healthcare, education, and social care. In the United States and the UK, the annual societal cost of ASD has already exceeded several billions [11]. User friendly and cost-effective therapeutic programs for autism can improve overall quality of life while reducing these costs. Recently, considerable advances have been achieved in using Information and Communication Technologies (ICT) such as multimedia, collaborative interactive environments, virtual reality, avatars, and robots in social skill training, especially for autistic children [5]. These technologies have demonstrated useful in training skills of emotion recognition from facial expressions and body languages, however, there exists insufficient evidence about whether the use of these technologies can improve face-to-face social interaction in naturalistic situations [15].

Recent work has leveraged technological advances to create wearable solutions for real-world social interactions with the support of real-time sensing, inference, and delivery of *in situ* social cues via multimodal feedback. However, these solutions have not been tested in long-term real-world use. Technical challenges, such as guaranteeing that these technologies can always derive in-time, accurate cues with reliability in varied contexts, may inhibit this kind of longitudinal study. Similarly, the ethical and privacy concerns, particularly for those bystanders who may be captured by the technology without deriving any benefit from it [18], can be challenges for novel assistive technologies. Finally, designing technologies that fully engage the autistic user experience – especially the impact of potential sensory impairments, multi sensory integration, and attention challenges, and more importantly support social inclusion, can be extraordinarily difficult. To support this kind of thoughtful design, particularly in the wearable assistive technology (WAT) space that focus on assisting interaction during social situations and conforming to social norms, this paper reviews the existing WATs for autism published in main-stream conferences and journals on wearable technologies, human-computer interaction, and pervasive and ubiquitous computing, and outlines current trends, main challenges, and future research directions.

2 Background on Social and Sensory Challenges in Autism

Even though ASD presents a wide spectrum of behavioural disorders, social communication difficulties are considered as a core feature that in its various manifestations tends to be universal in individuals across ages and language disabilities[2]. Such difficulties are characterised in the following two main areas.

[1]In this paper, we will use the disability-first language such as "autistic people" to describe people on the ASD spectrum, as this is the one favoured by autistic adults and families [14].
[2]Diagnostic and Statistical Manual of Mental Disorders, fifth edition, 2013, by American Psychiatric Association.

- **Social interaction and communication** – difficulties of attending and responding to social cues and understanding others' emotions. This is partly because autistic people may not be able to make direct eye contact with their conversation partners, nor spontaneously follow the direction of others' gaze thereby failing to jointly attend with others. Their attention focuses on the lower face region or the mouth of their conversation partners, which makes them only understand literally the others' speech while not being able to interpret social meanings or recognising mental and emotional states that are often reflected in the eyes.
- **Stereotypical behaviour** – repetitive interest and/or motor or vocal sequences that appear to an observer to be invariant in form and without any obvious eliciting stimulus or adaptive function [9]. The most prevalent stereotypical motor movements identified are body-rocking, mouthing, and complex hand and finger movements. These behaviours can appear socially inappropriate and stigmatising, which can complicate social integration of autistic people in school settings and the community. Also autistic people might be engaged in these behaviours for long periods – thus interfering with the new skill acquisition.

Sensory processing and attention Autistic people can suffer sensory processing impairment problem [1]; that is, they can be hyper- or hypo-sensitive to incoming sensory information. They might also have difficulties of shifting attention; that is, once their attention is switched to a certain stimuli, it will be difficult for them to disengage from it.

There exists vast individual difference between autistic people in terms of aspects and degrees in their social communication difficulties and as well as their sensory processing impairment. This diversity brings extra challenges in the design of a WAT as it needs to acknowledge and identify individuality and provides services adaptively.

3 Existing wearable assistive technologies for autism

Social skill training has long been one of the main objectives in many therapeutic programs for autism; that is, to teach typical and expected social interactions that enable adaptive responses in a variety of social situations [19]. Recently many therapists and specialists have opted for the integration of ICT in social skill training for autistic people to facilitate the delivery of training programmes [5]. On the one hand, these early studies in a well-controlled environment have been considered as a safe and enjoyable experience. Not only are they designed in an entertaining and engaging way, but also do not impose expectation and judgement as autistic people usually encounter in real social interactions. On the other hand, this computer-human interaction does not solve the problem of impaired human-human interactions, as the report in [5] shows that most of these technologies have not been validated beyond proof of concept studies. There is therefore little evidence showing that the skills practised in such controlled environments can be applied to real-world environments, so their use is still at an early exploration stage.

To achieve the generalisation of social skills, Klin *et al.* in the enactive mind theory [16] have suggested that autistic people need to accumulate experience in a vast number of cases, which presents a challenge to the traditional social skill training or closed-environment-based assistive technologies. With the advance in recent sensing, intelligent, and interactive technologies, it is potentially feasible to bring social skill training, therapy, and intervention to naturalistic situations by providing real-time, *in situ* feedback on their social interactions. This presents an opportunity for autistic people to accumulate cases and generalise social skills of their own over time. In the last ten years, a number of WAT prototypes have been developed for autism, which covers both social interaction and communication, and stererotypical behaviour challenges.

3.1 Emotion recognition

The early prototypes for real-time emotion recognition are composed of a wearable camera to capture live video feeds about social interactions occurring in real-world environments, and a mobile device to infer emotional or mental states about the people who autistic people interact with. These systems can provide *just-in-time* feedback to autistic people to suggest socially appropriate response or actions to their current social situations [27], and as well as act as a post analytic tool to review their social experiences; for example, how their expressions were perceived by their friends and how one might change their facial expressions to demonstrate a particular idea [17]. These prototypes have been mainly tested in a well-controlled environment. First of all, they often involve multiple hardware components, which makes them inconvenient to be used in non-controlled environments. Secondly and more importantly, the authors in [27] have pointed out that the systems have not achieved high reliability to be used outside of lab settings, given that people might depend on the system to react in social situations. If the system produced inaccurate social cues, it would have misguided or confused people and thus led to undesirable consequences.

With the recent advance in wearable technologies, we find wearable devices or gadgets that integrate both sensing and computation components into a single hardware device, which presents an opportunity to bring technologies closer to naturalistic environments. Washington *et al.* have designed and built a system called SuperpowerGlass [22] for automatic facial recognition using Google glasses. The system can detect social cues such as eye contact and facial expression recognition through the camera embedded in Google glasses and deliver the detected cues via audio or visual feedback. Over a 3-month trial with 14 families at home, the glasses have demonstrated to be a useful learning aid that has improved social behaviours of autistic children.

3.2 Eye contact detection

Eye contact and joint attention is another key aspect in social skill training, especially for autistic infants and toddlers. Ye *et al.* [25] have used commercial mobile eye tracking glasses mounted with a camera to automatically detect patterns of mutual eye contact and joint attention between parents and children. The joint attention is measured in the periods between both child and his/her parent in which they are looking towards each other and then towards a common area. They have evaluated the performance of the system in measuring gaze behaviour with children who are diagnosed with developmental disorders in a lab setting and the results have shown that the system is good at estimating the gaze direction while not so effective at detecting eye contacts.

3.3 Proximity and distance

Autistic people often lack an ability to sense and respond appropriately to the physical distance between individuals during social interactions; that is, where to stand, or what is an appropriate distance between them and others [7]. To address this challenge, Boyd *et al.* have designed a wearable system, called Procom, to draw users' attention on the distance they are holding from their interlocutors in a conversation [7]. To use the system, a user needs to wear at chest height the ProCom box that is composed of two infrared sensors and a servomotor. The IR sensors sweep between -30° and 30°, and record distances between the user and surrounding objects. A filtering process then runs against the recorded distance to derive the distance between the user and their interaction partner, which will be visualised in an aerial view on a mobile device, indicating whether the user is within a comfortable social space. This system can be very useful in therapeutic environments but it would be challenging if used in a real-life situation. The provided feedback can be distracting, too, as the user needs to constantly check the mobile application to see if he/she is within the right distance.

3.4 Atypical prosody

The acoustic quality of one's voice and prosody may be unusual and result in misinterpretation of a form of nonverbal communication. Examples of atypical prosody in autism are speaking in a flat tone or in a too loud voice. These challenges appear to contribute negatively to the social perception of autistic people and the overall social interaction experience. To support awareness of atypical prosody, Boyd *et al.* have developed a system built on Google glasses, called SayWAT [6]. The system can constantly monitor the voice volume and pitch of users and provide alerts when atypicality is detected. Based on the detected volume and pitch, the glasses trigger alerts either via plain text or an animation with a colour spectrum from green to yellow to red to indicate the severity of the situation.

3.5 Stereotypical behaviours

Autistic people often exhibit behavioural peculiarities that can promote their social isolation or increase their difficulties in social situations. One example of this is the occurrence of stereotypical behaviours. Westeyn *et al.* [3] have made an early attempt by using wireless Bluetooth accelerometers to be worn on the right wrist, the back of the waist, and the left ankle of a person, and a Hidden Markov Model to recognise seven types of stereotypical behaviours. The system has demonstrated promising recognition results, but there is no report on evaluating with autistic people. Going further, Albinali *et al.* [4] have also used wireless accelerometers to recognise a similar set of stereotypical behaviours, and evaluated the accuracies of the recognition algorithms on 6 autistic children in both lab and classroom settings. Their system has achieved a fairly good accuracy, but found difficult to recognise short episodes of stereotypical motor movements or subtle movements due to increased general activities.

3.6 General social skill

The majority of existing WATs target one aspect of the social interaction challenges. The exception is MOSOCO [12] that targets a range of social skills and is built on the social compass curriculum – a behavioural and educational curriculum covering 24 core lessons from basic nonverbal communication to more complex social problem solving. MOSOCO is a mobile application that augments a real-life social situation captured with a smartphone's camera and provides with visual and verbal support; for example, based on the eye contact detection result, the system can suggest autistic children to look at their partner's eyes. The experiments have been done in a school environment and have demonstrated promising results in enhancing interactions between autistic children and typically developing children.

3.7 Summary

Table 1: Different WATs for assisting social interactions of autistic people

WATs	**Targeted social challenge**	**Device**	**Feedback**	**Intended use and environment**
[27, 17]	emotion recognition	wearable camera + PDA/mini-computer	user interface on mobile application	a therapeutic tool for analytic and intervention in clinic and home settings
[22]	emotion recognition	smart glasses	real-time visual feedback, *e.g.*, text, colour, or emoicon	a real-time feedback tool for naturalistic situations
[25]	eye contact and joint attention	eye tracking device + camera	not available	a therapeutic tool for analytic and intervention in clinic settings
[7]	proximity	infrared sensors	user interface on mobile application	a therapeutic tool for analytic and intervention in clinic settings
[3, 4]	stereotypical behaviour	accelerometers	not available	a therapeutic tool for analytic and intervention in clinic settings
[6]	atypical prosody	smart glasses	real-time audio and visual feedback, *e.g.* a text message or color animation	a real-time feedback tool for naturalistic situations
[12]	social skill curriculum	smartphones	user interface on mobile application	a therapeutic tool for school setting

Table 1 has listed the above mentioned WATs for autism, which have evolved from the early prototypes trying to provide technological solutions to gather data in real-world situations for analysis as a part of therapeutic or intervention programs, to real-time assistance. These technologies have also evolved from self-assembled devices with sensing, computation, and interaction components (such as camera combined with a PDA or mini-computer [27, 17], or accelerometers with a mobile device [3, 4]) to a more integrated solution like smart glasses [6, 22].

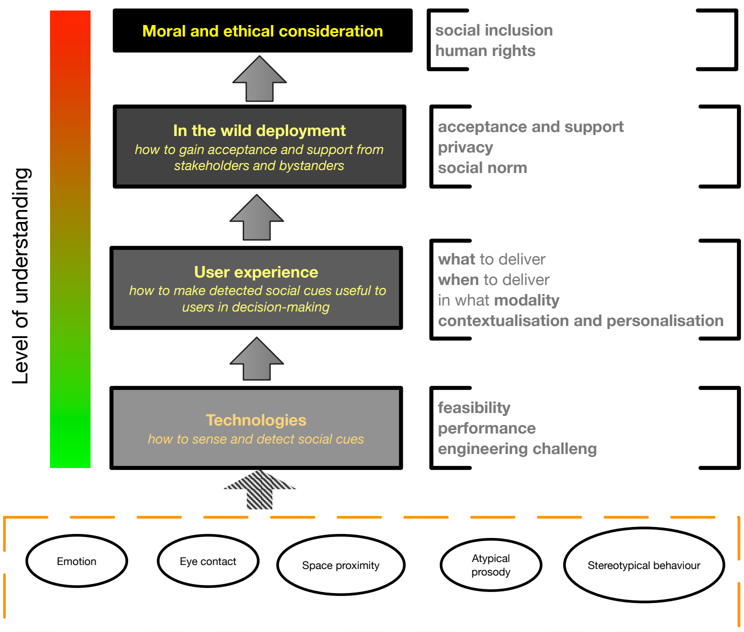

Figure 1: A landscape of WAT research development with the spectrum on the level of understanding in the current research community and the progression of main research activities along with their key research questions

As presented in Figure 1, at this early stage, research has focused on the **technologies** with the main questions on how to sense and detect social cues for autistic people including what their own behaviours are (*e.g.*, do they speak or behave in an atypical way), where they and their partners look and whether they share the attention, and what others' emotional/mental states are. All these form into the first step of WAT design, concerning about *feasibility* (*i.e.*, can we detect certain cues), *performance* (*i.e.,* how accurately can we detect), and *engineering* challenge (*i.e.*, can we assemble everything together, ideally into a wearable device, to be carried and used in real-world environments without much interference to people's normal tasks).

Once we can sense and detect social cues, then the next question will be how to make detected social cues useful to autistic people in decision-making. To address this question, we need to start considering **user experience** that plays a critical role on the effectiveness of WATs. There is a growing awareness of this aspect and recent projects like SayWAT [6], ProCom [7], and SuperpowerGlass [22] have explored different modalities of delivering real-time feedback. Going further, more questions can be probed around feedback; for example, what information to deliver, when, and in what modality. Addressing these questions needs to take into account characteristics and individuality of autism, such as their potential sensory impairment, multi sensory integration, and attention challenges, and thus to explore how to personalise and contextualise feedback delivery.

When we have the technologies and plan to deploy them **in the wild**, then questions might not just be centred around users or technologies, but everyone else being directly and indirectly interacted and impacted and co-living in the environments and communities. Then the research questions will be about how to gain acceptance and support from bystanders and stakeholders in different roles. Inspired by the recent *Disability Studies*, researchers are starting to re-position their purpose of a WAT design from a fundamental **moral and ethical** perspective [26]: whether a WAT should help autistic people (or in general people with disability) follow the same social norm or it should embrace their difference and empower them to find their own way. This part is least understood, even though we have achieved a reasonably good understanding of technologies and started to consider user experience, as indicated in the level of understanding in Figure 1. In the next section, we will give a more detailed discussion on these new research questions.

4 New research opportunities and challenges

Even though presenting as a promising approach, the current wearable assistive technologies are still at an early stage, from capturing to delivering meaningful and holistic social cues.

4.1 Social cue interpretation

Interpreting social meaning is a complex, open-domain task, which not only includes capturing facial expressions, body gestures, verbal and prosodic cues, but also needs to take into account situational contexts. The most well-recognised emotions from the state-of-the-art social signal processing algorithms might be happiness and anger [24], which however some autistic people, at least high functioning ones, have no difficulties in recognising. It is the subtle emotional states and complex mental states that autistic people struggle with, including disgust, frustration, and confusion. To our limited knowledge, the performance of recognising these states from spontaneous emotions in naturalistic situations has not achieved satisfactory accuracies [24] to be reliably used in the wild. One of the obstacles might be the scarcity of training data in naturalistic situations. It is a notoriously expensive undertaking to collect such a dataset, not to mention annotating them in an objective, reliable and quantitative way [29].

Recent advances in computer vision, speech analysis, and machine learning [10] make it possible to recognise fine-grained emotional and cognitive states from facial expressions such as frowns and pain, subtle body language or gestures such as tilting the head, and variations of emotions expressed through voice such as changes in rhythm and energy in vocal utterances. Each of these presents one aspect of the social world; however, it is necessary to combine and integrate all these different sources of cues to generate a reliable assessment of social situations [21]; for example, an emotion is considered "expressed via a sophisticated synchronised response that incorporates peripheral physiology, facial expression, speech, modulation of posture, affective speech, and instrumental action" [10]. Developing such multimodal systems is challenging and largely under-explored, due to the difficulty of modelling fusion on multiple time scales and of modelling temporal correlations within and between different modalities [21]. Recently, researchers in social signal processing have started exploring temporal relationships between different modalities like vision and audio using Long Short-Term Memory networks [23].

Context plays an important role in understanding social signals, including different types of social events and venues, social and cultural norms, and background context such as age, gender, and ethical group, and even individual differences. For example, a smile can have different social meanings in different contexts, such as a greeting when meeting people, a feeling of joy indicating that one is enjoying a conversation, or even an expression of irony [21]. The context factor is extremely difficult to compute and has remained a major challenge faced in the current research of social signal processing.

4.2 User experience

To make a WAT useful in naturalistic situations, we need not only to design sensors and algorithms to infer social cues, but also more importantly consider how users perceive, interpret, and respond to the inferred cues; that is, what information should be delivered, when and how often, and through what medium.

4.2.1 What and when to deliver

Choosing the right information to deliver to autistic people is not a trivial task. Social cues can cover a wide spectrum of information. Take an example of emotion recognition. A system might detect a smiling face, a shaking head, and low energy in voice in a group social situation. What would be the message delivered to a user? Each piece of information indicates one aspect of social cue and each might be able to impact our social behaviours differently. Delivering all of them might cause an information overload, with people getting confused and not knowing which feedback message to respond to.

Another important research question is *when* to deliver feedback. From the technological angle, the SuperpowerGlass project has employed a filter on the emotion recognition results in order to reduce the fire-rate and avoid false positives or rapid switching between similar emotional type [22]. The SayWAT project has designed their device to provide feedback only when necessary [6]; that is, delivering reminding feedback when atypical prosody is detected. However, in the future, the design consideration should be emphasised on users. For example, the utility of information is bounded by *Yerkes-Dodson Law* – the delivered information might only be able to help people to improve their performance in decision making up to a certain point. Over that point when information becomes excessive, performance diminishes. To identify this point in the context of WATs for social support for autism needs to be further explored.

In summary, what and when to deliver information to users can be a very challenging task; that is, finding right moment to deliver right information so as to guarantee the usefulness of information to users and more importantly, reduce the stress autistic people experience yet allow growth of skills. It not only requires the machine learning techniques to reliably produce correct information, but also requires us to **re-think of new methodologies on how to explore the way users learn to interact and make use of information over time**.

4.2.2 In what modality to deliver

The existing feedback modalities consist mainly of a text message (e.g., "anger") [22], a cartoon icon representing an emotional state [22], a colour or colour animation pattern (e.g., a bright red colour indicates anger), a voice speaking out an emotion, or a subtle beep or monolithic sound [6]. They aim to attract people's attention to make sure that people receive the message, however, over-attraction might cause negative effect on autistic people in social situations. First of all, some of these choices like bright colours or animation with a colour spectrum might cause anxiety, panic attack or even a feeling of aggression to some autistic people [30].

Secondly, these WATs have not fully taken into account sensory processing impairment introduced in Section 2. The over-attraction to feedback might distract people' attention away from their conversations. The SayWat system has taken the micro-interaction design principle, where they have defined a delay interval of three seconds to allow people to disengage the feedback and return to conversation. The future feedback design should balance attention seeking and disengagement; that is, trying to make sure people receive information for decision making while not overly distracting them away from conversations.

Studies in psychology and neuroscience have demonstrated intact performance in response to tactile stimuli. Researchers have also used tactile feedback in behaviour intervention programs for ASD; for example, using a light touch on a customised force plate to help autistic children reduce their body sway and increase their body balance [2]. Therefore, tactile feedback can be potentially promising for WAT design to deliver social cues, while enabling users to stay focused on the visual and auditory dimensions of social situations. However, unlike a vocal or text message that can explicitly deliver information, tactile feedback is implicit and might present a challenge for delivering rich social cues. Therefore, one future work could be to design different tactile patterns to deliver social cues so that autistic people can intuitively understand without much cognitive overload and sensory overload while still able to concentrate on their ongoing conversations. Methodologies or experience can be drawn from *SensoryPaint* [20] to **explore how autistic people understand, perceive, interact, and integrate various modalities of feedback in their decision-making process and find out which way might best balance their attention between their own perception and delivered feedback**.

4.2.3 Contextualisation and personalisation

The majority of existing WATs tend to deliver universal feedback to all the users or for all the situations, which have not considered personalisation and contextualisation. However, autistic individuals might prefer different choices of colors or sound volumes [5] according to their own responsiveness and sensitiveness to sensory stimuli [1]. Or, they may appreciate different types of signals or respond differently to the signals depending on where they are (*e.g.*, public or private), who they are interacting with (*e.g.*, family, peers, or strangers), what the current social task is (*e.g.*, job interview or dating), and even what emotional states they are currently in (*e.g.*, happy or stressed).

An intelligent component can be introduced in feedback delivery – **how to learn users' preferences on information and feedback modality in different situations and adaptively select the most effective and appropriate strategy**. For example, a system could assess a user's emotional state or anxiety levels through psycho-physiological data and adjust to deliver more appropriate feedback; *e.g.*, decreasing the volume of a voice feedback, or switching the feedback modality from voice to haptic.

4.3 In the wild deployment

A long-term deployment in the field is not a trivial task at all, which often requires privacy, adaptation and social acceptability of these systems, and as well as the support from each stakeholder group [8]. Beyond general privacy and data protection concerns on how to control personal data sharing to ensure confidentiality and make informed consent while not undermining people's autonomy, we also need to **consider privacy of autistic people, their interaction partners, and even background bystanders** [28], as their information is being collected through artificial sensors. Therefore careful ethical decisions have to be made before designing a WAT.

4.4 Moral and ethical considerations

The design principle for WATs for autism has shifted in the research community over years: from building a social-emotional prosthetic for autistic people [13], to fostering transferable learning skills so that through the use of a WAT a user can eventually learn social skills without the constant need of the WAT [6, 22]. Still, all these WATs are designed from a "fixing-thing" perspective; that is, regulate behaviours of autistic people and train them to understand and follow the same social norms as everyone else. However, autistic people may have a different way of perceiving the condition and may not need or want assistive technologies. Some would prefer treating their sensory impairment not as a disability but a different way of behaving in relation to social stimuli. Taking a fundamental moral and ethical position [26], the future direction might look at **how to design wearable technologies to enable autistic people to find their own way in social situations, or design assistive technologies for both autistic people and their conversation partners to achieve mutual understanding**. For example, stereotypical behaviours are increasingly recognised as a positive coping mechanism for autistic people, and a future WAT might need to address its social acceptability; *e.g.,* allowing the others to understand.

5 Conclusion

Assistive technologies for social skill learning in general and wearable assistive technologies in particular have been a popular research topic over recent years. With the aid of a WAT, autistic people cannot only learn in a classroom or a clinical environment but also in a real-world environment with real-time feedback in diverse types of social situations. These advances represent an important step for improving the opportunity to integrate in society and be able to enhance understanding and awareness in different social situations.

As presented in Figure 1, with the increasing awareness of user experience, the spotlight on WAT design starts shifting from technologies alone to users. The change will have a fundamental impact on the design; that is, not simply considering what technologies can do, but begin to put more thought on what users need or prefer and then on how to make technologies better serve the purpose. Moving up the ladder, with the technologies being more and more mature, long-term in the wild deployment is becoming more and more feasible. Then we need to start considering a wider scope beyond technologies themselves but also the environments, user experience, and everyone else who might directly and indirectly contribute and impact on the delivery, and test these design principles with autistic people in the wild.

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