Skin Conductance as an *In Situ* Marker for Emotional Arousal in Children with Neurodevelopmental Communication Impairments: Methodological Considerations and Clinical Implications

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Even though electrodermal activity has been widely used in the study of psychological states and processes for over 130 years, the use of such technology *in situ,* within the context of daily activities, remains a major challenge. Recent technological advancements have led to the development of wearable biosensors that noninvasively measure electrical conductance across the skin. These biosensors represent a new approach for skin conductance assessment, as a proxy for emotional arousal, in children with neurodevelopmental communication impairments who are often described as having difficulties with emotional regulation, expressing thoughts and feelings, and present a higher prevalence of challenging behaviors. Here we provide an overview of skin conductance and explore the benefits of recent technological advancements for applied research and clinical practice. We draw on user experience from two experimental interventions involving eight children with neurodevelopmental impairments. In both cases investigators monitored phasic and tonic EDA measures *in situ* using wearable biosensors. We share the behavioral and technical challenges experienced across these two experimental contexts, and propose associated considerations for future use. Specifically, sensor functioning, synchronization, and data preprocessing/analysis difficulties, as well as behavioral findings related to developmental differences, sensor tolerance over time, and sensor placement are discussed.

CCS Concepts: • **Human-centered computing** → **Empirical studies in HCI**; *Field studies*; • **Social and professional topics** → **People with disabilities**; **Children**

Additional Key Words and Phrases: Electrodermal activity (EDA), skin conductance (SC), *in situ*, emotional arousal, neurodevelopmental communication impairments, autism, user experience

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1. INTRODUCTION

Electrodermal activity (EDA) has been widely used in the study of psychological states and processes for over 130 years [Boucsein 1993, 2012]. However, traditionally its use has been limited to highly controlled settings in research laboratories with restricted external validity, e.g., Figner and Murphy [2011], Stevens and Gruzelier [1984], and Williams et al. [2004]. Recently, wearable biosensors that noninvasively measure electrical conductance across the skin have been introduced, offering the opportunity to study skin conductance *in situ*, within the context of daily activities, e.g., Poh et al. [2010a, 2012]. Biosensors that measure EDA, among other biometrics, are already being commercialized and featured in mainstream media, with promises to "get the most out of your workouts" with the OM smart bra [OMsignal 2016], and to attain "a more calm, balanced state of mind" with Spire [2015]. More relevant to this particular article, such technology has been marketed as able to predict "outbursts in individuals with autism" [Violeta 2015] See also Curtis [2015], Kraft [2015], Stout [2015]. The biosensor wristband is projected to "allow carers to monitor physiological signals that may be indicative of an impending meltdown, thereby allowing them ample time to take appropriate actions" [Violeta 2015]. We contend that assessing skin conductance as a proxy for emotional arousal in children with neurodevelopmental communication impairments holds qualified promise in helping communication partners understand and interpret the perceptions and experiences of children with communication impairments. Despite promise, this technology is reaching the general public at a rate faster than associated guidelines for evidence-based practice.

This article provides an overview of skin conductance and identifies the challenges associated with assessing skin conductance in children with neurodevelopmental communication impairments *in situ*, leading to the development of considerations for practice and the accumulation of resources to facilitate future data collection and analysis. The present work stems from our experiences assessing *in situ* skin conductance in children with neurodevelopmental communication impairments during two experimental contexts: (1) a speech-language intervention study focused on increasing multisyllabic productions in children with speech-language impairments (SL-EDA study) (see Aparicio Betancourt et al. 2013 for SL-EDA feasibility study, see DeThorne et al. 2015 for larger behavioral intervention project); and (2) an occupational therapy study focused on examining the use of a pressure vest to increase academic engagement for two children with intellectual disabilities (OT-EDA study) [Snodgrass et al. 2015]. We briefly review prior preliminary EDA findings from these two studies and also present novel *post hoc* data analyses specifically related to the utility of this technology with children with neurodevelopmental communication impairments in clinical settings.

2. OVERVIEW OF SKIN CONDUCTANCE

EDA is a common term for the variation of electrical phenomena in the skin in response to sweat secretion, triggered by postganglionic sudomotor nerve fibers (i.e., sympathetic sweat motor nerve fibers, mediated by the neurotransmitter acetylcholine also referred to as *cholinergic innervation*) [Benedek and Kaernbach 2010a]. The relationship between skin sympathetic nerve activity and electrodermal responses is complex [Kunimoto et al. 1991, 1992], and is highly influenced by participant's thermoregulatory state [Wallin 1981]. When comfortable ambient temperature is maintained (usually 22–24°C), electrodermal activity has been shown to respond relatively slowly to sympathetic nerve impulses (i.e., usually 0.5–1.5 seconds and sometimes greater than 5 seconds), and the strength of the electrodermal responses also varies [Hagbarth et al. 1972; Kunimoto et al. 1991, 1992; Wallin 1981]. Differences in stimulus-response latency and sensitivity may be due to: interindividual differences in

Fig. 1. Sympathetic cholinergic (sudomotor) innervation predominantly mediates skin conductance.

thermoregulatory state, differences in conduction time (e.g., conduction may vary based on the recording site and participant's height), the requirement of duct filling or sweat production potentiation before triggering an electrodermal response, and local stimuli including hormonal and mechanical stimuli [Kunimoto et al. 1991, 1992; Wallin 1981]. Although direct nerve recordings provide a more sensitive measure of cholinergic sympathetic activity [Brown et al. 2012], electrodermal activity remains a reliable and well-validated indirect measure that offers the opportunity to assess sympathetic nervous system (SNS) activity non-invasively and *in situ*. Broadly, EDA can be measured by placing two electrodes on the surface of the skin with or without applying a small external electrical current, referred to as exosomatic and endosomatic methods, respectively. The use of EDA within psychological research has focused on exosomatic methods, recording skin resistance (R) or its reciprocal, skin conductance; R is equal to the voltage (V) applied between two electrodes placed on the surface of the skin, divided by the current (I) passed through the skin ($R = V/I$) [Boucsein 1993, 2012].

Changes in EDA may be caused by an increased or decreased demand for neural activity, including cognitive and emotional loads, and physical activity. Effortful allocation of attentional resources, stress, affect, hydration of the corneum (upper epidermal layer), and diurnal effects (i.e., EDA levels are sensitive to the time of day), are factors known to influence EDA [Boucsein 1993, 2012; Critchley 2002; Dawson et al. 2000, 2007; Nagai et al. 2004]. Specifically, an increase in cholinergic innervation (i.e., mediated by acetylcholine), as occurs for example in response to acute stressful stimuli such as being startled by a lightning bolt during sleep or in response to increased concentration due to increased task demands, leads to an increase in sudomotor SNS activity. This leads in turn to increased eccrine sweat gland secretion, and increased electrical or skin conductance that can be measured by biosensors (see Figure 1) [Benedek and Kaernbach 2010a; Squire et al. 2008]. Baseline electrodermal activity may also vary with individual differences in race, age, sex, body mass index, sweat gland density, and with use of medications and psychoactive substances including caffeine [Doberenz et al. 2011]. Electrodermal activity is measured as a one-dimensional time series signal and consists of two main phenomena: phasic and tonic.

2.1. Phasic Skin Conductance Response

The phasic skin conductance response, reaction (SCR) or peaks, is a transient increase in skin conductance elicited 1 to 5 seconds after stimulus onset; novel, unexpected, significant, or aversive stimulus have been shown to produce an SCR [Boucsein 1993, 2012; Dawson et al. 2000, 2007]. Consider, for example, an SCR elicited in a child who is first introduced to the shake of a tambourine, the sight of a toy snake, or the unexpected strobe light display at a museum. It is important to note, what may elicit an SCR in one person may not necessarily do so in another, and how our bodies respond to a stimulus may change over time or may vary based on context. For example, a

self-identified autistic[1] woman, Dr. Temple Grandin, describes craving the "good feeling of being hugged", but then she describes how she "stiffened and pulled away to avoid the all-engulfing tidal wave of stimulation" [Grandin 1992, 2013]. Temple Grandin may have experienced increased SCRs when hugged by others, compared to when she was at rest, and compared to a person who is not as sensitive to hugs.

In addition to specific phasic responses, there is spontaneous nonspecific phasic activity that cannot be linked to any specific stimulation. Nonspecific SCRs are most often used during continuous data collection, as it is difficult to link responses to specific stimuli. Nonspecific SCRs are considered a useful, indirect, index of sudomotor sympathetic activity, with higher frequency associated with higher levels of activity. The NS.SCR is frequently measured by both the amplitude and frequency of associated peaks, often ranging between 0.1–1.0 μS and 1–3 per minute respectively while at rest [Boucsein 1993, 2012; Dawson et al. 2000, 2007]. In general, nonspecific SCRs can be observed while at rest due to spontaneous activity, and are also associated with relatively mundane stimuli within our day to day, as well as in response to less mundane stimuli such as the abrupt loud sound of a fire alarm. However, it may be difficult to link responses to specific external stimuli when collecting data in uncontrolled applied settings. Consequently, all SCRs gathered during continuous data collection, such as applied settings, are considered nonspecific.

2.2. Basal Tonic Skin Conductance Level

In contrast to the phasic component, the basal tonic skin conductance level (SCL) is relatively stable and associated with gradual changes in skin conductance. SCL will be relatively high in novel environments and will decrease gradually with time; it is associated with both cognitive and emotional arousal. As an example, the SCL of a child during their first day of school might be significantly higher compared to their SCL on subsequent days of the school year. The SCL has also been shown to be lower during sleep and higher during activated states such as states of increased concentration like when you are solving a math problem or learning to play the guitar. The SCL is frequently measured by the overall tonic level of electrical conductivity of the skin or as a gradual change measured at two or more points in time, often ranging between 2–20 μS and 1–3 μS respectively [Boucsein 1993, 2012; Dawson et al. 2000, 2007].

2.3. Skin Conductance Measures

As previously mentioned, phasic skin conductance response is frequently measured by both the amplitude and frequency of associated peaks. Basal, tonic skin conductance is frequently measured by overall skin conductance level, or change in SCL. Less common measures include: SCR area under the curve (AUC; i.e., the total area between the SCR initiation and recovery of SCR amplitude); and SCL AUC (i.e., the total area between a specified window of time) [Boucsein 1993, 2012; Dawson et al. 2000, 2007]; see Figure 2 for an illustration of SC components and relevant measures). Correlations among EDA measures are generally moderate to low; however, the association between AUC and

[1]We acknowledge the different perspectives surrounding identity-first and person-first language and use both as a means to recognize and appreciate the different opinions, and to improve sentence clarity (see Autism & Oughtisms [2011] and Duncan [2011] for perspectives of parents of autistic children who use both identity- and person-first language). Advocates of identity-first language propose autism is not a negative quality and is a part of the person, central to a person's identity, and should thus be used as an adjective (see Hillary [2015] and Sinclair [1999] for perspectives written by autistic individuals). On the other hand, person-first language proponents view autism as a negative quality, as one of many traits of a person, that is not central to their identity, and believe using autism as an adjective leads to devaluation of the person and facilitates prejudice and discrimination (see Snow [2009] for a perspective of a mother of an adult with cerebral palsy).

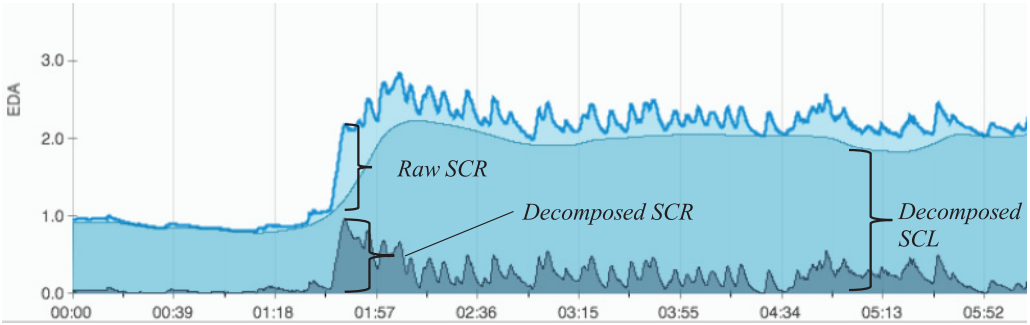

Fig. 2. EDA/SC data as graphically displayed by BEDA [Kim et al. 2013]. Light blue phasic SCR shows the SCR prior to SC decomposition (raw SCR). Dark blue phasic SCR and mid blue tonic SCL are the two components of SC post SC decomposition; SC = SCL + SCR.

the other EDA measures is largely undocumented. Such findings suggest that most of the EDA measures represent partially independent sources of information, although the neurological and psychophysiological underpinnings are not well understood.

2.4. Neural Mechanisms of Skin Conductance

The neural mechanisms and pathways involved in mediating EDA are numerous and complex and further research elucidating the central origins of EDA is needed. Eccrine sweat glands have been shown to be mediated at different levels of the central nervous system, by both ipsilateral (i.e., same side of the body) and contralateral (i.e., opposite side of the body) processes, which are partly independent of each other. Boucsein [1993, 2012] proposed three main central nervous system levels influencing EDA (see also Critchley [2002]):

(1) *Ipsilateral Limbic Hypothalamic Source*: Excitatory influences stem mainly from the hypothalamus, amygdala, and limbic system, whereas inhibitory influences stem from the hippocampus. The limbic hypothalamic source is thought to be influenced by both thermoregulatory and emotional processes.
(2) *Contralateral Premotor Basal Ganglia Source*: Independent of the first source and is composed primarily of excitatory and inhibitory influences originating on the premotor cortex, frontal cortex, and basal ganglia which mediate EDA in preparation of specific motor actions.
(3) *Reticular Formation (RF) Modulating System*: Both excitatory influences and inhibitory influences originate from the bulbar level of the RF on EDA, and may be eliciting or modulating influences that originate from the first two sources.

Generally, EDA during emotional tasks is thought to be mediated by the ipsilateral system, which may differentially influence eccrine sweat secretion [Mangina and Beuzeron-Mangina 1996], whereas EDA during nonemotional tasks is mediated by the contralateral system [Dawson et al. 2000, 2007]. Differential influence of the ipsilateral system on eccrine sweat secretion has been supported by a direct electrical stimulation study in humans [Mangina and Beuzeron-Mangina 1996]. SCRs elicited by direct stimulation of limbic structures, the amygdala in particular, via intracerebral electrodes in five adult neurosurgical patients, yielded a higher amplitude compared with those elicited from cortical areas, with higher ipsilateral than contralateral responses. Specific to the neural systems associated with the phasic skin conductance response see Critchley [2002]; Dawson et al. [2000, 2007]; Mangina and Beuzeron–Mangina [1996]; Nagai et al. [2004]; and Vetrugno et al. [2003]. Although there has been

disproportionately less research examining the neurological underpinnings of the basal tonic skin conductance level readers are referred to Nagai et al. [2004].

2.5. Past and Common Uses

Recent advances in the development of biosensors have led to watch-like bands with embedded electrodes that noninvasively measure electrical conductance across the skin by passing a small amount of direct current between two electrodes in contact with the skin (bipolar recording) such as the Q sensors [Affectiva 2012] and E4 sensors [Empatica 2016b]. In addition to measuring skin conductance (microsiemens, μs), such sensors may also measure temperature (Celsius), actigraphy (g-force, g), and photoplethysmography (which measures blood volume pulse from which cardiovascular measures such as heart rate can be extracted).

With the increased ease of EDA measurement has come a variety of new uses. In particular, EDA has been used in conjunction with functional magnetic resonance imaging (fMRI) to examine sympathetic activity during the decision-making process [Figner and Murphy 2011], as well as its association with implicit fearful experiences [Williams et al. 2004]. One of its most promising areas is the potential to manage epilepsy [Empatica 2016a; Nagai and Critchley 2008] and predict seizures, particularly generalized tonic-clonic (GTC) seizures [Poh et al. 2012; Ramgopal et al. 2014].

In addition to such interesting venues, the use of EDA data may be particularly useful for better elucidating the everyday experiences of children with neurodevelopmental impairments, especially those who experience significant communication difficulties. Although EDA varies widely across subjects, it is relatively stable within subjects, and changes in EDA within subject are associated with different psychological states [Boucsein 1993, 2012; Dawson et al. 2000, 2007]. Consequently, monitoring EDA may assist in understanding children's response to various environmental conditions. One basic tenet, specified by the Yerkes-Dodson Law [Yerkes and Dodson 1908], states that human performance increases as physiological arousal increases up to an optimal arousal point, beyond which it decreases; thus, representing a quadratic equation shown in an inverted-U curve. As such, EDA could help provide valuable information regarding how to best fashion educational environments to facilitate children's comfort and learning. More recently, researchers have also predicted it can be used to detect meltdowns in children with autism [Curtis 2015; Kraft 2015; Stout 2015; Violeta 2015]. However, additional research is warranted investigating the use of biosensors to measure *in situ* skin conductance in applied settings.

2.5.1. Benefits of EDA Assessment in Children with Neurodevelopmental Communication Impairments. Utilizing EDA to understand emotional arousal could be particularly useful for children who frequently encounter communication challenges. Neurodevelopmental communication impairments impact as many as 19% of children [Nelson et al. 2006] (See also ASHA [2014] and Pinborough-Zimmerman et al. [2007]), including diagnoses of autism spectrum disorders, social (pragmatic) communication disorder, language delay or disorder, childhood apraxia of speech, and severe speech sound disorders.

Moreover, children with neurodevelopmental communication impairments are often described as having difficulties with emotional regulation and reported to have a higher prevalence of challenging behaviors. Redmond and Rice [1998] report a 50–70% co-occurrence between language impairments and socio-emotional difficulties, most likely due in part to communication challenges. Challenging behaviors include both externalizing behavioral problems such as physical aggression (e.g., hitting, kicking, biting), verbal aggression, oppositional behaviors (e.g., running away), and internalizing behavioral problems such as anxiety, depression, and social withdrawal cf. Qi and Kaiser [2004]. Studies suggest that interventions aimed at understanding the feelings

and intentions of individuals with communication challenges are likely to decrease the frequency and severity of challenging behaviors [Gainey 2013; Halle et al. 2006; Hemmeter et al. 2006; Hutchins and Prelock 2014]. Our hope is that measures of physiological arousal could aid in better understanding the emotional arousal levels and corresponding emotions of children with neurodevelopmental communication impairments in order to build better environments to support their learning and social interaction.

Sensory Integration Differences in Children with Autism. Electrodermal activity assessment might be particularly useful for children with communication and sensory integration difficulties, such as many children with autism. In fact, hyper/hyporeactivity to sensory input or unusual interest in sensory aspects of the environment is a diagnostic feature for autism spectrum disorders as detailed in the Diagnostic and Statistical Manual of Mental Disorders, fifth edition [APA 2013], and is commonly reported by autistic adults [Grace 2015; Fleischmann and Fleischmann 2012]. Stevens and Gruzelier [1984] assessed EDA (i.e., SCL and SCRs) in a controlled laboratory setting and demonstrated that levels of skin conductance were slightly higher in autistic children compared to neurotypical children and those with intellectual disabilities (ages 7–17 years) in response to auditory stimuli, thereby providing evidence for a tendency toward heightened physiological arousal. In addition, the children with autism showed reductions in peak amplitude, longer response latencies and rise times in response to 70dB tones, indicating a slower habituation and relative delay in stimulus registration (see also Ming et al. [2005]). Moreover, differences in skin conductance in response to another person's gaze have also been reported in children with autism, with increased SCRs associated with straightforward gaze compared with averted gaze [Kylliainen and Hietanen 2006]. Differential pattern of SCRs to the two gaze conditions was not seen in children without autism. Together, such results support the sensory integration differences often reported in individuals with autism [Tomchek and Dunn 2007], and suggest that EDA data might be useful in adjusting intervention environments.

2.5.2. In Situ EDA Assessment.

Behavioral Sciences. Despite the recent technological advances in EDA, few studies have examined *in situ* EDA in children with communication impairments within the behavioral sciences, and the impact of intervention on children´s emotional arousal is relatively unexplored. Hedman [2010] was the only study we found that examined EDA during intervention, and it was largely observational in nature. Specifically, EDA was measured using a biosensor known as iCalm in 22 children with sensory processing disorder during particular guided occupational therapy activities. Each child participated in three to eight guided activities per session and analyses were based on approximately 50 total one-hour sessions. The lack of an experimental control, the lack of normalization of the data, and the low power led to inconclusive results. However, the researchers highlighted results from individual children in response to specific stimuli. For example, one child demonstrated increased emotional arousal when playing in the ball pit, whereas another child demonstrated significant decreases during the same guided activity. The study highlighted the importance of case study methodologies that can assess and accommodate children's individual differences.

Similar to Hedman [2010], Miller et al. [2007] examined EDA in children undergoing occupational therapy. However, skin conductance was not assessed during the intervention; instead, SC was continuously recorded during the Sensory Challenge Protocol before and after treatment. The Sensory Challenge Protocol consisted of a series of 50 sensory stimuli administered to the participants. Miller et al. [2007] conducted a pilot randomized controlled trial in 24 children with sensory modulation disorders to assess the effectiveness of occupational therapy using a sensory integration approach. Even

though group comparisons had limited power, were nonsignificant, and 54% of the EDA data had to be discarded, their results indicated greater reduction in SCR amplitude in children in the treatment condition compared with the children in the active and non-active control groups suggesting reduced hyper-reactivity.

Human Computer Interaction. Although a large number of studies have investigated ways to automatically identify individuals' stress levels (e.g., Healey and Picard [2005] and Sano and Picard [2013]), engagement levels (e.g., Hernandez et al. [2014]), and various emotions such as happiness (e.g., Jaques et al. [2015]) using EDA and other physiological data such as heart rate in individuals without communication impairments, fewer studies within computer science have explored the use of such systems in individuals with neurodevelopmental communication impairments. More recently, several technological applications have been developed to measure EDA in conjunction with eye gaze measures and measures of social communication in autistic individuals, to better understand how their physiological levels change when demonstrating challenging behaviors or during social interactions [el Kaliouby and Goodwin 2008; Lee et al. 2008; Riobo et al. 2014]. The goal of these systems is to support communication by providing caregivers of individuals with autism and autistic individuals themselves with alternate methods to observe their levels of emotional arousal in real-time during social interactions. Reviewing EDA levels synchronized with video data of challenging behaviors or day to day social interactions could potentially be used to provide biofeedback to autistic individuals to facilitate processing social information and facilitate regulating emotional arousal levels prior to engaging in challenging behaviors.

For example, Lee et al. [2008] developed a wearable platform to detect face contact using a hat-mounted wireless camera while measuring EDA via a wrist-worn sensor. The researchers conducted a usability study with four autistic adolescents and their caregivers to explore how the system could be improved to be used to quantify social stimuli and the associated stress response, as measured by skin conductance. Findings illustrated various limitations of the system including the need to develop a more flexible system that provides information in real-time. In fact, one of the caregivers who participated in the study suggested that real-time visualization of physiological states of people with autism "would be helpful in understanding students' arousal states and in teaching self-regulation" [Lee et al. 2008]. With a similar motivation, the Interactive Social-Emotional Toolkit (iSET) [el Kaliouby and Goodwin 2008; Madsen 2010] was developed by combining a wearable camera, that can be worn as a self-cam or a head-cam, and a wrist-worn sensor to capture video, audio, and physiological data (i.e., skin conductance, heart rate, and movement) concurrently. Young autistic adults have participated in the early design stages and used prototypes of the wearable system that captures multimodal data. The goal of this technology is to facilitate the processing of high-speed and complex social information such as nonverbal cues, by providing autistic adults with the opportunity to systemize, quantify and reflect on their own social interactions via a fun and engaging tool. Finally, Riobo et al. [2014] developed a system that sent a real-time visualization of an autistic child's EDA to the Google glass unit (*Google Inc*.) worn by their caregiver, while the two were interacting together. The system aims to help caregivers interact with their children by gaining a deeper understanding of the child's internal state and their individual experience of the social interaction. These different technologies however, have yet to be evaluated in a large-scale basis or in in-depth qualitative, descriptive studies evaluating user experience.

Although technological applications and computational methods have been developed and have shown promise of using EDA to understand and predict behaviors in individuals whom are often difficult for their partners to understand, there is limited

Table I. SL-EDA Participant Demographic & Biosensors Information

Participant Pseudonym	Gender	Age	Race	Primary Clinical Diagnosis	Q Sensor Placement	Total # of sessions[a]	# Desensitization Sessions[b]	% Sessions Sensor Worn[c]
Pyrros	Male	2;7	White	Unspecified Developmental Delay	Left & Right Ankle	37	1	97%
Dora	Female	2;11	Asian	Autism	Left & Right Wrist/Ankle	9	0	89%
Angelo	Male	3;0	White	Speech Sound Disorder	Left & Right Ankle	24	8	67%
Heidi	Female	3;8	White	Autism	NA	25	25	0%
Karis	Male	4;8	White	Autism	Right Wrist	20	5	60%
Pan	Male	4;11	White	Autism	Left & Right Ankle	3	2	33%

[a]Total # of sessions refers to the total number of sessions, including both treatment (tx) and evaluation sessions, in which the participant was exposed to the sensor(s);
[b]# Desensitization Sessions refers to the number of sessions the child was exposed to the sensor(s) prior to wearing it for at least half the tx session (i.e., 22.5 minutes);
[c]% Sessions Sensor Worn refers to the percentage of sessions at least one sensor was worn for at least half the tx session (i.e., 22.5 minutes).

research investigating and/or reporting the challenges in using wearable sensors to assess *in situ* EDA in children with neurodevelopmental communication impairments [cf. Boucsein 1993, 2012; Doberenz et al. 2011; Turpin et al. 1983]. For example, wearing a novel object, such as a sensor, could be a challenging task in itself for children with autism and/or sensory difficulties. In this way, we aim to provide methodological considerations for assessing short-term *in situ* skin conductance based on investigator experience working with children, ages 2–11, with neurodevelopmental communication impairments across two applied experimental contexts.

3. EXPERIMENTAL CONTEXT

This section of the article introduces the two experimental contexts used to inform our considerations for use of biosensors *in situ* with children who have neurodevelopmental communication impairments: skin conductance assessment during speech-language therapy, followed by a study assessing skin conductance during occupational therapy. Specifically, we provide a brief overview of the purpose, method, and results associated with each study, with an explicit focus on novel *post hoc* data analysis related to use of the biosensors to collect EDA during behavioral intervention.

3.1. SC Assessment during Speech-Language Therapy

This feasibility study, hereafter referred to as the SL-EDA study, assessed the associations between *in situ* EDA recordings and off-line behavioral coding of emotional valence (EV) and examined the association among different EDA measures [Aparicio Betancourt et al. 2013].[2] The study represents a subset of participants ($n = 6$) from a larger project that examined the effectiveness of a speech-language intervention for children at the single-word stage of development [i.e., DeThorne et al. 2015]. Participant demographic and novel behavioral data regarding biosensor use within the SL-EDA study is presented in Table I by participant (identified by pseudonyms). The first author served as one of the intervention therapists for all participants except

[2]SCL. AUC is referred to as SC.AUC in Aparicio Betancourt et al. [2013] but should read as SCL.AUC.

Fig. 3. Left panel: Affectiva Q Sensor [Affectiva 2012]. Mid panel: Child practicing target words with VocSyl, a software developed to provide online visual feedback during the motor practice portion of the intervention; biosensors are placed on his ankles and are not visible. Right panel: Child engaged in a naturalistic interaction during developmental play targeting the bisyllabic word, *tiger*; biosensors are placed on his left and right ankles.

Karis, and all sessions were video-recorded. Note that Dora and Pan withdrew early from the larger intervention study, and Heidi never tolerated wearing the biosensors.[3]

EDA was measured in microSiemens (μS) and recorded from dry Ag/AgCl disk electrodes at a sampling rate of 8Hz using the Affectiva Q sensor v1 as long as children were willing to wear the biosensors (see Figure 3, left panel). The biosensors were fitted at the wrist or ankle based on participant tolerance and preference was given to the dominant wrist/ankle as it yielded a higher amplitude compared to the nondominant wrist/ankle (see Román et al. [1989] for similar results, see Picard et al. [2016] for significant EDA asymmetry, with greater amplitude in dominant wrist); for consistency, only data from the dominant wrist/ankle were analyzed. Although EDA data collected at the wrist yielded slightly higher responses compared to the ankle, sensor location attempted to increase the participant's comfort level and decrease distractions (see Payne et al. [2013], for similar results). Collection of EDA data at both the wrist and the ankle do not interfere with daily activities and have been shown to be accurate and strongly correlated with more traditional Palmar sites of EDA measurement [Fletcher et al. 2010; Picard et al. 2016; Poh et al. 2010b]. The biosensors were calibrated to be the same within study. The number of sessions participants were exposed to the sensor(s) prior to wearing them for at least half the treatment session (i.e., # desensitization sessions), and the length of the desensitization procedures varied by participant based on sensor tolerance (see Section 5.1 for a review of the desensitization techniques). Even though dry electrodes were used, to improve signal acquisition electrode gel was placed on each electrode, and children participated in a biosensor acclimation process which involved a period of activation followed by a rest period intended to bring the children's physiological arousal level back to a theoretical baseline. Following the biosensor acclimation process, children participated in a motor practice session that involved repetitions of multisyllabic speech productions (e.g., *butterfly*, *tiger*), and a developmental play session in which those same words were modeled and elicited during child-centered play-based activities (Figure 3) (see DeThorne et al. [2015] for additional treatment details). The average session length for the SL-EDA study was

[3]Dora's family moved out of state and Pan's mother reported that he was already overcommitted with other activities.

55 minutes (i.e., 10 minutes for the biosensor acclimation process and 45 minutes for therapy).

Consistent with prior literature [Boucsein 1993, 2012; Dawson et al. 2000, 2007; Hernandez et al. 2014], the EDA measures assessed included nonspecific skin conductance response frequency (NS.SCR.freq) per minute, nonspecific skin conductance response amplitude (NS.SCR.amp), and an additional less-traditional measure, nonspecific skin conductance level area under the curve (SCL.AUC). SCRs were detected using an amplitude threshold $\geq .01$ μs and a minimum distance between responses of at least 1 second. SCL.AUC was calculated using 1-minute consecutive windows from the start of the session to the end of the session. The thermostats at the clinical facility were set at a comfortable ambient temperature, approximately 71°F (22°C), and all analyzed intervention sessions were held at the same time each day within participant. EDA data were analyzed for participants who completed the speech-language intervention and wore the biosensors (i.e., Pyrros, Angelo, Karis). Although EDA data were collected across both treatment and evaluation sessions, data were analyzed for treatment sessions only due to differences in activity. Data from 33% (21/63) of all treatment sessions had to be discarded due to (a) sensors not worn or tolerated for at least half the session (11/21, 52%), (b) low signal-to-noise ratio associated with loss of electrode contact with the skin due to physical activity, such as jumping and hand flapping, and participant manipulation with the sensors (5/21, 24%), (c) malfunctioning sensors or synchronization difficulties (4/21, 19%), and (d) sessions being held at a different time of the day (1/21, 5%). The percent of sessions with useable EDA data by child was 91% (29/32) for Pyrros, 61% (11/18) for Angelo, and 15% (2/13) for Karis. Consistent with signal processing and continuous skin conductance processing [Benedek and Kaernbach 2010b, Boucsein 1993, 2012; Dawson et al. 2000, 2007; Hernandez et al. 2014], EDA analyses followed a three-step process: (1) visual inspection of 10% of synchronized treatment sessions with EDA recordings using ELAN,[4] (2) data pre-processing (visual inspection of all EDA recordings, cropping, manual artifact rejection, and smoothing), and (3) SC decomposition into continuous phasic SCR and tonic SCL components using BEDA[5] [Kim et al. 2013] and MATLAB. Actigrahy (3-axis accelerometry) and skin surface temperature data were used to aid synchronization, visual inspection of the data, and manual artifact rejection. In addition to assessing emotional arousal, emotional valence was assessed by conducting off-line behavioral coding of all treatment sessions for which EDA data were analyzed. Specifically, emotional valence was rated every minute based on an examiner's video review of the child's vocalizations, facial expressions, and corporal gestures, using a 1–5 Likert scale (1 = high negative affect, 5 = high positive affect).

As a brief overview of results from the SL-EDA study, associations between *in situ* EDA and off-line behavioral coding of emotional valence were examined by polynomial regression for all treatment sessions. NS.SCR.freq was significantly higher for high positive and negative off-line behavioral coding of emotional valence ratings compared to neutral ratings ($b = .53$, $p < .01$) though the effect size was small (adjusted $R^2 = .023$, $F(4, 1{,}337) = 8.78$, $p < .001$). Although significant, NS.SCR.freq explained very little variance in behavioral ratings of emotional valence (<3%). Consistent with the general trends recorded in other studies for the average physiological responses for children who were more difficult to engage [Hernandez et al. 2014] or for children introduced to novel stimuli [Dawson et al. 2000, 2007], both NS.SCR.freq ($b = .14$, $p < .001$) and SCL.AUC ($b = .20$, $p < .001$) significantly increased over time

[4]ELAN is an annotation tool that allows you to converge multi-media recordings (Brugman and Russel [2004[, MPI [2016[, see Berez [2007[for a review).

[5]BEDA is a visual analytic tool to help synchronize, visualize, and analyze data sources for multiple sessions of behavioral and physiological data.

Table II. OT-EDA Participant Demographic and Biosensors Information

Participant Pseudonym	Gender	Age	Race	Primary Clinical Diagnosis	Q Sensor Placement	Total # of sessions[a]	# Desensitization Sessions[b]	% Sessions Sensor Worn[c]
Damien	Male	9;8	Black	Intellectual Disability (ID)[d]	Left & Right Ankle	37	0	100%
Calvin	Male	11;6	White	Autism, ID	Left Ankle	23	0	100%

[a]Total # of sessions refers to the total number of sessions, including both observation and treatment (tx) sessions, in which the participant was exposed to the sensor(s).
[b]# Desensitization Sessions refers to the number of sessions the child was exposed to the sensor(s) prior to wearing it for at least half the tx session (i.e., 7 minutes).
[c]% Sessions Sensor Worn refers to the percentage of sessions at least one sensor was worn for at least half the tx session, (i.e., 7 minutes).
[d]Damien had secondary diagnoses that included physical impairment, complex partial seizures and absence seizures.

within session though with fairly small effect sizes[6] (NS.SCR.freq: adjusted $R^2 = .019$, $F(2, 1{,}339) = 13.66$, $p < .001$; SCL.AUC: adjusted $R^2 = .053$, $F(2, 1{,}339) = 38.75$, $p < .001$). In regard to associations across EDA measures, consistent with prior research, results indicated a significant moderate correlation between NS.SCR.freq and NS.SCR.amp ($r = .48$, $n = 42$, $p < .01$). In contrast, the association between SCL.AUC and other EDA measures is largely undocumented. Results indicated a significant high correlation between NS.SCR.freq and SCL.AUC ($r = .85$, $n = 42$, $p < .001$), and a significant moderate correlation between NS.SCR.amp and SCL.AUC ($r = .44$; $n = 42$, $p < .01$), suggesting SCL.AUC and NS.SCR.freq may be mediated by similar psychophysiological or neurological sources.

3.2. SC Assessment during Occupational Therapy

The second experimental context reviewed here is a single-subject reversal design study (A-B-C-A) focused on examining the effects of a pressure vest on academic engagement, challenging behaviors, and skin conductance in two children with developmental disabilities [Snodgrass et al. 2015], hereafter referred to as the OT-EDA study. The use of pressure vests and other sensory integration techniques are common practice within occupational therapy for individuals with increased needs for proprioceptive/tactile input as a means to help regulate physiological arousal [Barton et al. 2015; Hodgetts et al. 2011; Lang et al. 2012; Reichow et al. 2009]. The use of biosensors was included to assess EDA as a dependent variable, in addition to behavioral measures. Participant demographic and novel behavioral data regarding biosensor use within the OT-EDA study is presented in Table II by participant (identified by pseudonyms). All sessions were video-recorded.

In contrast with the SL-EDA study, the OT-EDA study collected electrodermal activity at a sampling rate of 32 Hz using the Affectiva Q sensor v2. In addition to the functions present in Affectiva Q sensor v1 used by the SL-EDA study, v2 offered wireless capabilities via Bluetooth connection. The sensor could transmit data between the Q sensor and a computer in real-time for visualization using Q Live Software. However, only data from the internal card data were analyzed (see Section 4.2.1 for further details). The biosensor(s) were fitted on the ankle and secured with an ankle wrap. Similar to the SL-EDA study, preference was given to the dominant ankle and only data from the dominant ankle were analyzed. Sessions consisted of a biosensor

[6]Although the general protocol of the speech-language treatment sessions remained the same, children engaged in a variety of activities during the latter half of the session consisting of developmental play and were therefore not habituated to the stimuli (see DeThorne et al. [2015] for treatment details).

Fig. 4. Left panel: Child engaged in a communicative exchange, using his speech-generating device, prior to the treatment session; biosensor is placed on his left ankle and secured with an ankle wrap. Right panel: Child putting toys into a container targeting fine-motor skills during occupational therapy; biosensors are placed on his ankles and are not visible.

acclimation process followed by occupational therapy activities individualized to each participant's goals, such as fine motor skills (e.g., self-feeding with a fork) and cognitive skills (e.g., counting, sorting objects by attributes such as color)(Figure 4) (see Snodgrass et al. 2015 for additional treatment details). The reversal-design (A-B-C-A) consisted of three main conditions: unpressurized vest, structured teaching (condition A); unpressurized vest, unstructured teaching (condition B); and pressurized vest, unstructured teaching (condition C). The average session length for the OT-EDA study was 24 minutes (i.e., 10 minutes for the biosensor acclimation process and 14 minutes for therapy).

Consistent with prior literature [Boucsein 1993, 2012; Dawson et al. 2000, 2007; Hernandez et al. 2014], the EDA measures assessed included mean NS.SCR.freq per minute per session, mean NS.SCR.amp per session, and mean skin conductance level (SCL) per session. SCRs were detected using an amplitude threshold ≥ 0.05 μs and a minimum distance between responses of at least 3 seconds. Mean SCL measures an average of all the collected SCL values (32 hz per second) across a treatment session. Mean SCL was highly correlated with mean SCL.AUC ($r = .90$). All analyzed intervention sessions were held at the same time each day within participant. EDA data were analyzed for the one participant who reached a stable baseline for behavioral measures and wore the biosensors (i.e., Damien). Although EDA data were collected across both observation and treatment sessions, data were analyzed for Damien's treatment sessions only, for a total of 25/30 (83%) treatment sessions, as observation sessions were conducted for desensitization purposes. The observation sessions were used to gradually pair the sensors with feelings of relaxation or excitation prior to the onset of treatment sessions to accustom children to wearing the sensors. Data from the remainder 17% (5/30) of the sessions had to be discarded due to (a) sessions ending early due to health concerns related to Damien's seizure diagnoses (3/5 = 10%),[7] and (b) low

[7]Damien also presented seizure activity before and/or during 10 out of the 25 treatment sessions analyzed. These sessions were not discarded because Damien was able to safely participate for the majority of the duration in each of these treatment sessions. Although SCL ($M = 4.16$ μs, $SD = 1.93$ μs), NS.SCR.amp ($M = 0.09$ μs, $SD = 0.07$ μs) and NS.SCR.freq per minute ($M = 0.23$, $SD = 0.2$), were lower for the seizure days than for the non-seizure days (SCL: $M = 4.28$ μs, $SD = 1.92$ μs; NS.SCR.amp: $M = 0.15$ μs,

signal-to-noise ratio associated with extremely low electrodermal responses (<0.7 μS) based on a criterion of one standard deviation away from the mean (2/5 = 7%). EDA data analysis followed a similar 3-step process compared with the SL-EDA study with one major difference: all of the video-recorded treatment sessions were synchronized with EDA recordings and visually inspected using BEDA compared to the 10% of the sessions in the SL-EDA study (see Section 3.1).

As a brief overview of results from the OT-EDA study, the interventionist's instructional practices (i.e., structured v. unstructured) appeared to play a more direct role in child engagement for Damien than did use of the pressure vest based on visual inspection as is consistent with single-subject design. Specifically, Damien remained engaged approximately 85% of the time and presented challenging behaviors approximately 10% of the time during the structured instruction phases, compared to 34% and 69% respectively during the unstructured instruction phases. In addition, use of the pressurized vest was not significantly associated with EDA based on *Mann-Whitney U tests* across conditions, and associations between EDA levels and child engagement or challenging behaviors were inconclusive. Readers are referred to Snodgrass et al. [2015] for a more detailed account of the findings.

4. METHODOLOGICAL CONSIDERATIONS

4.1. Behavioral Findings across Studies

The present section summarizes children's responses to use of the biosensors across both the SL-EDA and OT-EDA studies. Given the age and linguistic ability of the participants, we relied on video-recorded behavioral data from the participants and direct interviews from the research assistants regarding their experience with the technology. In particular, an additional coding pass was conducted across available video data in order to review participant's behavioral response to wearing the Q sensor(s). The first author conducted an explicit review of at least 10% (n = 3) of all sessions for each child across the two studies (Range = 11%–100%), including the first two sessions and the last session. Video-recorded sessions included observations, evaluations, and treatment sessions. Additionally, to gain better insight on the user experience of the investigators, the first author conducted semi-structured interviews with the three lead research assistants across the two studies face-to-face or by telephone. Data were analyzed by the first author following qualitative thematic methodology guidelines [Braun and Clarke 2006] including familiarization, development of themes, and developing an analytic narrative. Observation notes were taken during the interviews and all interviews were audio-recorded and transcribed. Orthographic transcription consisted of three levels of coding: the first two levels were conducted by an individual transcriber trained to replicate pauses, non-speech sounds, overlapping speech, and unintelligible speech; the second level allowed the transcriber to verify the accuracy of the original transcription. The purpose of the third coding level was to reach consensus across two transcribers on the transcript sections with unintelligible speech. After becoming familiar with the interview data, the first author conducted a preliminary analysis of the data to identify codes and themes among the data related to behavioral challenges, technical challenges, and recommendations. Finally, the first author reviewed the preliminary analysis and re-reviewed all interview transcripts to identify themes and extract representative excerpts across the aforementioned categories.

SD = 0.15 μs; NS.SCR.freq per minute: M = 0.37, SD = 0.20), a *Mann-Whitney U test* indicated that scores were not significantly different.

Despite substantial individual variability, three noteworthy themes emerged in regard to behavioral challenges associated with sensor use: (a) developmental differences, (b) sensor tolerance, and (c) sensor placement.

4.1.1. Developmental Differences. First, younger children required a period of acclimation/desensitization to the biosensors before wearing them. All the children below the age of 5, with the exception of Dora, required at least one desensitization session (Median = 4) whereas our two oldest participants across studies, ages 9 and 11, wore the sensors during the initial session and did not show any visible signs of discomfort. Dora was our first participant across both the SL- and OT-EDA studies and was a child who was largely nonverbal. She appeared highly reluctant to wearing the sensors at first. When initially introduced to them, she pulled her hand away and squirmed to avoid having the sensor placed on her wrist. "Just a little bit. Ok?" her mom remarked. Once the sensor was on her wrist, as quickly as possible, the clinicians diverted her attention by inviting her to bounce on a green stability ball. As Dora's facial expression began to relax and once again smile, the clinicians resumed placing the other sensor on. Once again, Dora began to squirm and then vocalize, and finally tried removing the sensors with her mouth. However, as soon as her attention was diverted away from the sensors and towards the stability ball, Dora instantly engaged in the ball activity by constant laughing as the clinicians and her mother sang, "bounce, bounce Dora. . .Dora likes to bounce!"

4.1.2. Sensor Tolerance. A second notable finding is that despite initial reluctance by many of our younger participants, ages 2 to 4, the majority of children started wearing the sensors consistently in subsequent sessions (Median = 61% of sessions). Our two older participants, ages 9 and 11, wore the sensors consistently across all sessions (Median = 100%). For example, from the second session onwards Pyrros began to spontaneously ask for the sensors "papa watch?" and to voluntarily participate in the process of putting the sensors on and placing them under his socks. Angelo's reaction to the sensors went from abrupt, unanticipated crying in the initial session to wearing the sensors for the entire 45 minutes of the ninth treatment session. As described by Angelo's lead clinician when asked to describe the process of using the sensors in the SL-EDA study, "I know for a second [Angelo] was getting freaked out and started screaming and crying and wouldn't have anything to do with [the sensors], but after that . . . one of the first things we did was . . . let him work out which one he wanted to put on first . . . and then we would strap 'em on there . . . and then he would wear them for the duration of the session."

Despite such success, there were two notable exceptions to the developed tolerance of the sensors over time: Karis and Heidi. Karis, as described by his mother was "obsessed" with watches, which hold close resemblance to the Q sensor. Karis enjoyed exploring the sensor and placing it on and taking it off his wrist starting with the second session. He showed a preference for placing the sensor on his wrist, and did not tolerate the sensor on his ankle. Unfortunately, Karis' interest in the sensor distracted him during therapy, and it was often put aside by the clinicians to be able to target the speech and language treatment goals. As reported by Karis' clinician when prompted to describe the children's response to the sensors, she explained, he "was just distracted by [the sensor], he kinda just wanted to play with it . . . he liked to put the watch on himself . . . and he always wore [it] pretty loose too . . . that sometimes was a challenge when he was struggling with it and you know we needed to get on . . . with the treatment session". Because of the constant manipulation of the sensor, paired with repetitive motor mannerisms (e.g., arms and hand flapping and posturing, and up and down bouncing), a high percentage of the EDA data collected during the times he wore the sensor for at least half of the tx session had to be discarded due to low signal-to-noise

ratio (SNR) (5/8 = 63%). That is, he wore the sensor for 22.5 minutes in 8 of his 13 tx sessions, and 5 of those 8 tx sessions were discarded due to low SNR, even though he wore at least one sensor for at least half the session for 12 of his 20 sessions (including both tx and evaluation sessions), and for all of his sessions in the second half of the intervention (i.e., session 11–20). Heidi, on the other hand, did not seem to trust the sensors. Even when the sensors were placed on family members she seemed protective of her loved ones and would immediately remove the sensors from them. Through a gradual desensitization process, she allowed the sensors to be placed on her ankles for a few seconds but would quickly remove them. Although a variety of strategies were used as an attempt to have Heidi wear the sensors during therapy, including a social story (see online appendix), Heidi never did tolerate wearing the sensors on either the wrist or ankle for an extended period of time; she did not wear either sensor for at least half the session (i.e., 22.5 minutes) for any of her 25 sessions.

4.1.3. Sensor Placement. A third and final behavioral trend worth noting is that the sensors were better tolerated on the ankle secured with either an ankle wrap or socks than on the wrist. In addition to changing the "feel" of the biosensor, such cover might also make it more likely that children forget they have it on, decrease the likelihood of children becoming distracted by the sensor throughout the session, as well as decrease movement artifacts associated with loss of electrode contact with the skin, often caused by physical activity (such as walking, running, or other repetitive motor mannerisms). In the words of one of the SL-EDA clinicians, once the sensors were on the children's ankles, "the kids could put them under their socks . . . you know they kinda would forget about them and not be messing with them or be distracted by them." In Dora's case, placing the sensors out of sight, under Dora's sleeves and particularly under her socks and pants was helpful; Dora seemed to barely notice them in such cases. She went from squirming to completely disregarding the sensors when placed on her ankles instead of on her wrists. Given that Dora tolerated the sensors on her ankles more so than on her wrist; we continued to attempt to place the sensors on her ankles and opted to do the same for all subsequent participants. We also encouraged caregivers to dress their child with long pants or sleeves. Ultimately, sensor location varied by participant based on individual participant's preference and tolerance.

Even though the investigators moved towards placing the sensors out of sight, many of the younger children, including Angelo and Karis, often became distracted by the intermittently flashing light displayed on the sensor. This led them to manipulating the sensor, increasing the artifacts in the data, and on occasion the children removed the sensors. Instead of relying solely on whether or not the participants wore socks and/or long pants during the session to hide the sensors from sight, whenever the child was not wearing socks or to avoid having to tighten the sensors too much due the short length of the sensor strap, the clinicians in the OT-EDA study secured the sensors with an ankle wrap.

In sum, children tolerated the sensors better when placed on the ankle. Although younger children required a period of desensitization to the biosensors before wearing them, most of our participants started wearing the sensors consistently in later sessions and older children consistently wore the sensors throughout all of the sessions.

4.2. Technical Findings across Studies

Similar to the behavioral findings, noteworthy themes related to technical challenges were derived from behavioral observation of the video-recorded sessions and the semi-structured interview data. In support of the point that technical challenges were significant and impinged on the data collection, 4% (4/93 sessions) of the data were discarded due to technical challenges, keeping in mind there would have been substantially more

data loss if only one sensor would have been available during data collection. Given two sensors were available during data collection, researchers were able to collect data when one of the two sensors malfunctioned (i.e., if the dominant wrist/ankle sensor malfunctioned, the second sensor could be placed in the dominant wrist/ankle in order to collect data). Moreover, all investigators, including those with prior signal processing experience, reported encountering several technical challenges during the research process.

Across the two experimental contexts, the following three main themes associated with technical challenges emerged: (a) sensor functioning, (b) synchronization, and (c) data preprocessing/analysis. Of interest, three sessions were discarded due to sensor functioning and one session was discarded due to synchronization challenges.

4.2.1. Sensor Functioning. Specific to sensor functioning, investigators had difficulty getting the sensors to begin recording data after fitting the sensors on the child during the initial evaluation sessions. Based on the Affectiva Q User Manual [2013] the "Q Sensor is ideal for long-term use because it works without the use of gels"; instead, Q sensors use dry electrodes. However, without the use of electrolyte, even after engaging in a task that stimulated cognitive, emotional, and physical activation, the sensors would not start logging data automatically or manually for the first few minutes. As a result, in order to improve signal acquisition investigators in the SL-EDA study continued using an electrode gel as the conductive medium between the electrodes and the skin during all treatment sessions. One of the lead clinicians in the SL-EDA study explained, "to get the sensors to conduct" we "figure[d] out to put just a little bit of gel on there ..." Investigators in the OT-EDA study subsequently adopted this practice as well. Moreover, OT-EDA investigators also experienced difficulties visualizing and recording data in real-time via Bluetooth. The real-time data were not reliable because (a) the Bluetooth was often disconnected and (b) data resulted in a drift.

In addition to difficulty with data recording, technical challenges related to sensor functioning also included accessing the data and sensor malfunctioning. Specifically, investigators across both experimental contexts had difficulties with Windows computers failing to recognize the sensor as an external device and as a result were initially unable to access the data. Upon contacting customer service, investigators in the SL-EDA study were informed this occurred due to "the number of directories in the root exceed[ing] a threshold" of approximately "20 dated folders" (Affectiva Support, pers. comm.). Also across the course of both studies, one of the two sensors stopped recording data and required repair. Although the reason for malfunctioning in the OT-EDA study was never resolved, the device in the SL-EDA was shipped back to the manufacturer for repair in the midst of data collection. The reason for the malfunctioning noted by the manufacturer was that the sensor's secure digital (SD) memory card became dislodged from its housing (Affectiva Support, pers. comm.).

4.2.2. Synchronization. The second theme of technical challenges associated with use of the sensors across both studies related to synchronization of electrodermal activity with audio-video recordings. As specified by one investigator from the OT-EDA study when asked about the technical difficulties encountered during the study, "the *huge* difficulty was to synchronize the video and the sensor data streams because the [camera] and the sensor technology work separately so we had to time it and [use] different software programs to synchronize" it. To assist with the synchronization process, investigators across the two studies used several strategies; consequently, the synchronization process resulted in more of an art than a science. Specifically, investigators utilized audiovisual cues from the video recording, the event-mark buttons on the sensors, and the accelerometer data to assist with synchronization. Finally, the internal clock of the sensor was compared to the time the session started, indicated

by the video data (synchronization strategies are highlighted in the considerations for practice (Section 5.2.3)). Unfortunately, two main challenges arose that made the synchronization process between the EDA data and video more difficult. One, children were very interested in exploring the sensors and would often press the event-mark buttons on the sensors, and two, the internal time of the sensors was not exactly synchronized with real-time. Initially, investigators in the SL-EDA study used ELAN to assist with synchronization of the visual and the EDA data but the software proved unreliable and would often "freeze" and "crash". In contrast, investigators in the OT-EDA study were able to use BEDA to assist with the synchronization process successfully, a program that was specifically designed for this purpose by one of the investigators.

4.2.3. Data Preprocessing/Analysis. The third area of technical challenge that emerged in relation to use of EDA data was related to data preprocessing and analysis. Even though EDA has been used widely for over 130 years, reliable software to analyze *in situ* continuous EDA data is still in development and with little in the way of standardized procedures (cf. see Boucsein [1993, 2012] for the most comprehensive review of psychological applications, mechanisms and methodology of EDA). Even without ELAN's freezing and crashing episodes, the software was not able to do what the investigators across studies wanted to do such as comparing many sessions at the same time. Initially, investigators across the two studies ended up having to use multiple software programs for multiple purposes, such as using one program to synchronize the video and EDA data and another to crop the EDA data. Even the investigator with prior signal processing experience had difficulty pre-processing and analyzing the data with the available software programs (e.g., Ledalab). When asked about the software available to analyze the EDA data, the OT-EDA investigator acknowledged she "had some difficulties importing the signal" and difficulties in general, "that's why" BEDA was developed [Kim et al. 2013], to assist with visualization, synchronization and analysis of the data.

5. CONSIDERATIONS FOR PRACTICE

5.1. Behavioral Considerations: Desensitization Techniques and Additional Behavioral Strategies

Being exposed to a novel object by a new person in an unfamiliar environment can be quite difficult for many children, particularly children with neurodevelopmental impairments who may be particularly sensitive to certain stimuli and have difficulty understanding and being understood by others. Desensitization procedures have been successfully used to reduce anxiety in children when exposed to novel technology. To illustrate, Barnea-Goraly et al. [2014] successfully used a brief behavioral training with children ages 4–10 during MRI scans as a means to eliminate the use of sedation to acquire motion-free high-quality images.

Behavioral findings across the SL and OT EDA studies suggest younger children (2–4 years) with neurodevelopmental communication impairments require a period of desensitization to the biosensors before wearing the biosensors. Based on our data, we recommend that investigators using similar biosensors allow at least four desensitization sessions, prior to data collection sessions, for children below the age of 5. Although older children may require less time and attention to the desensitization process, we recommend planning at least one desensitization session when working with children, particularly those with marked impairments or differences. Consequently, we offer here the explicit desensitization techniques we used to acclimate children to the sensors (see Table III for a summary of the behavioral considerations). Desensitization procedures have been defined as "pairing of either graduated imagined or graduated external stimuli with either relaxation or other responses competitive with anxiety" [Hatzenbuehler

Table III. Behavioral Considerations for Short-Term *In Situ* Skin Conductance Collection and Analyses using Wearable Biosensors with Children with Neurodevelopmental Communication Impairments

General Considerations
—Use desensitization procedures when exposing children to novel technology. At least one desensitization period/session is recommended for children over five years; younger children are likely to require more (≥4).
—Out of sight, out of mind: place sensors out of sight, preferable on the ankles, and wrap each sensor with a brace. Each sensor should have a snug but not a tight fit as it should fit the child comfortably.
Present Biosensors in a Graduated Hierarchy, Progressively Increase Exposure to the Biosensors
In- home Exposure:
—Developing and reading a social story (see online appendix)
—Fit the child with bracelets/watches (or sensors) around ankles/wrists at home for increasing periods of time
On Site Exposure to Biosensors:
—Encourage the caregiver to actively participate in the desensitization process
—Incorporate a picture of the sensors in the child's visual schedule of the session's activities
—Reread social story at the onset of sessions
—Draw comparisons between bracelets/watches used at home and sensors (e.g., it is just like Papa's watch!)
—Encourage child to explore the sensors (e.g. make note of the flashing light) and provide reassurance
—Place the sensors first on the therapist/researcher, then on the caregiver and finally on the child. If the child is apprehensive, move the biosensors incrementally closer to the child and encourage the child to wear the biosensors for a specified period of time (e.g., 2 seconds. Count the seconds out loud and/or use a timer for visual support (e.g., hourglass, iPad app)).
Gradually Pair Positive Valence Responses with the Biosensors
—Introduce the sensors to the child when the child is in a positive affective state (e.g., excited, attentive)
—Decorate the sensors, e.g., with stickers or other decorations to make them more appealing to the child
—Refocus the child's attention to a preferred activity (i.e., one that promotes positive affective states)
—Use reinforcement procedures such as if-then statements, verbal and non-verbal praise for attempts, and game playing
Create an Environment Conducive to Positive Valence Responses
—Build rapport and trust with the child
—Tailor the strategies & reinforcers used to the child's individual needs and preferences
—Introduce new activities and reinforcers for novelty as needed, and make the sessions as engaging and enjoyable as possible!

and Schroeder 1978] as a means to decrease the anxiety associated with the stimuli, and are common in disciplines such as special education and psychology. Consistent with systematic desensitization procedures [Hatzenbuehler and Schroeder 1978; Ollendick and Cerny 1981, 2013], our desensitization procedures focused on presentation of stimuli (i.e., the sensors) in a graduated hierarchy, gradual pairing of the positive valence responses with the sensors, and in creating an environment conducive to positive valence responses.

5.1.1. Presentation of Biosensors in a Graduated Hierarchy. To desensitize children to wearing the sensors, we recommend presenting the sensors in a graduated hierarchy, progressively increasing the child's exposure to them. Prior to direct expectations to wear the sensors (i.e., in-home exposure), caregivers were encouraged to read to the child a social story we prepared to explain the process of wearing the biosensors. Consistent with the use of social stories, often used to familiarize children with developmental disabilities to behavioral expectations in new situations and to reduce challenging behaviors, the stories were written from a first-person perspective and included photographs as visual supports [Gray and Garand 1993; Moudry Quilty 2007; Swaggart et al. 1995]; see online appendix for our specific example. In addition to being asked to share the story with their child, caregivers were encouraged to fit their children with

bracelets/watches around ankles/wrists at home – based on intended sensor placement – for increasing periods of time to provide their child with the opportunity to experience sensations similar to those they will experience when wearing the sensors. They were also encouraged to bring the bracelets/watches to the initial sessions for visual support when drawing comparisons with the sensors.

Desensitization techniques employed during direct exposure to the sensors (i.e., utilized during the observation, initial assessment and treatment sessions) included rereading the prepared social story, providing reassurance, and additional strategies to gradually familiarize children with the sensors. This included incorporating a picture of the sensors in the child's visual schedule of the session's activities [cf. Mirenda and Brown 2009], introducing the biosensors as a watches/bracelets,[8] and providing a period in which children were encouraged to explore the biosensors themselves, gradually increasing exposure to the sensors consistent with systematic desensitization literature. Specifically, the investigator might draw the child's attention to different aspects of the sensors, such as the flashing light. If the child is hesitant to touch the biosensors at all, an investigator might begin by manipulating them themselves and subsequently putting them on the caregiver's wrist/ankle during initial presentation. The presence of the child's caregivers during the initial sessions also served to increase comfort. Other suggestions might include moving the biosensors incrementally closer to the child's wrist or ankle or encouraging the child to wear the biosensors for a specified short period of time (e.g., 2 seconds) and count the seconds out loud or use a timer (e.g. hourglass, iPad app) for visual support, which can be progressively increased in time.

5.1.2. Gradual Pairing of Positive Valence Responses with Sensors. As a means to gradually pair the sensors with positive valence responses, investigators introduced the sensors to the child when the child appeared to be in a positive affective state (e.g., interested, excited, proud, and attentive vs. negative affective states such as upset, scared, and nervous). The biosensor itself can also be decorated with stickers or other images and colors to make it more familiar and appealing to the child. For example, we decorated Dora's biosensors with images of Dora from "Dora the Explorer" after learning she highly enjoyed watching the show at home during the initial assessment session prior to the start of therapy. Similarly, refocusing attention from the biosensors to a favorable activity that elicits responses competitive with anxiety, such as excitement or relaxation, might be helpful (e.g., "Let's go bounce on the ball!", "time to play with the iPad", "time to read your favorite book"). Finally, reinforcement procedures in which children were rewarded by their parents or clinicians after wearing the sensors were also used. For example, Pan was taken to the pool, a favored activity for him, after the sessions (e.g., "*If* you wear the sensors, *then* we can go to the pool after speech" would be an example of delayed reinforcement). Verbal and non-verbal praise for attempts and game playing were also used to provide immediate positive reinforcement (e.g., sensors are introduced when child appears to be in a positive affective state → child wears sensors → adults clap, smile, cheer, provide specific verbal praise, and provide child with tangible reinforcer such as the iPad).

5.1.3. Creating an Environment Conducive to Positive Valence Responses. Finally, we focused in creating an environment conducive to positive valence responses. For example, caregivers were asked to provide information regarding their child's preferred activities and objects/toys, individual child's preferences were informally assessed throughout

[8]Excerpt indicating how clinicians across the studies introduced the sensors to the children: "These are bracelets/watches [show child sensors] that feel and look very similar to your bracelets/watches [point to child's bracelets/watches they wore at home]. They will give us information about your feelings. For example, they will tell us whether you are excited or relaxed."

the intervention, and new activities and objects/toys were introduced for novelty. By the end of the study, children and the investigators grew mutually fond of one another. This was evidenced by children expressing their desire to continue with therapy after being told it was clean-up time, and by caregiver's unsolicited report of the children inquiring about their clinicians while at home.

Whatever specific procedures are employed, it is important to anticipate the need for individualized responses. Children are likely to respond differentially to the same strategy. For example, whereas gradually increasing contact with the biosensors worked wonderfully for Angelo, this same strategy was not effective for Heidi.

5.2. Technical Considerations

5.2.1. Factors that May Influence EDA. In situ or ambulatory skin conductance assessment has made major advances over the last decade but continues to require close monitoring of the multiple factors that may influence the data including ambient temperature, time of day, physical activity, and individual differences (e.g., race, age, sex). In addition to requiring careful monitoring, decreased ability to control such factors requires careful selection of the preprocessing and analysis methods and careful interpretation of the results. Consequently, few *in situ* EDA studies have been published to date. Of those reported, some offer only superficial assessments of EDA and/or had to discard a high percentage of the data. For example, Miller et al. [2007] monitored EDA while administering a series of sensory stimuli in 24 children with sensory modulation disorders and had to discard 54% of the EDA data and provided few details regarding EDA data analysis. Doberenz et al. [2011] assessed multiple factors known to influence SC during a 24-hour period *in situ* and concluded that although feasible, some measures need to be corrected for the influence of confounding variables. Other reports on problems of long-term *in situ* EDA recording have found the conducting medium or gel to significantly influence EDA recording, with a hydrating medium leading to fewer and smaller SCRs compared to a non-hydrating medium [Turpin et al. 1983], and have even concluded ambulatory recordings to lack both reliability and validity after 24 hours, although this particular study had low power and did not conduct statistical comparisons [Boucsein et al. 2001]. Given difficulties with wet electrode use in long-term ambulatory SC assessment, dry electrodes are also available.

Although research examining short-term ambulatory SC poses fewer challenges compared with long-term ambulatory SC recording (e.g., electrode deterioration is less of a concern), it poses challenges nonetheless. Overall, it is important to note skin conductance tends to vary widely across subjects (i.e. high inter-individual variance) and is more stable within subjects [Dawson et al. 2000, 2007]. It is also important to highlight that the same factors (e.g. physical activity) may influence between-subject comparisons and within-subject comparisons differentially [Doberenz et al. 2011]. Researchers interested in assessing skin conductance need at least a basic understanding in signal processing, time series data, and in the physiological basis of electrodermal activity and are referred to Boucsein's [1993, 2012] electrodermal activity book for a more thorough review and Dawson and colleagues' [2000, 2007] chapter on electrodermal activity in the handbook of psychophysiology for a shorter review. The remainder of this section will provide recommendations and references based on the factors likely to influence short term *in situ* monitoring of EDA including ambient temperature, time of day, physical activity, and individual differences but it is by no means inclusive, and its intended purpose is to make readers aware of some of the factors needing special consideration. Here we offer explicit considerations to address the technical challenges encountered (see Table IV for a summary of the technical considerations).

Ambient Temperature and Time of Day. In regards to ambient temperature and time of day, recording in a temperature-controlled setting during the same time of day

Table IV. Technical Considerations for Short-Term *In Situ* Skin Conductance Collection and Analyses using Wearable Biosensors with Children with Neurodevelopmental Communication Impairments

General Considerations
—Researchers are recommended to become familiar with the following electrodermal activity resources: Boucsein [1993, 2012]; Dawson et al. [2000, 2007]
Control for Factors that may Influence EDA, including:
—Ambient temperature and time of day (i.e., record data in a temperature-controlled setting (usually 22°C–24°C), during the same time of day)
—Physical activity (e.g., walking, running, bouncing, jumping and/or other repetitive motor mannerisms such as hand flapping)
—Individual differences (e.g., age, sex, race, body mass index and sweat gland density)
—Use of medications and psychoactive drugs (e.g., caffeine)
Sensor Functioning
—Collect data using two sensors (one on each side of the body), and ensure at least one other sensor is available for data collection in case one malfunctions.
—Use internal storage over bluetooth: bluetooth was often disconnected and data collected resulted in a drift
—Given data across sensors are comparable: Use dominant wrist/ankle to yield higher amplitude. Use nondominant site to decrease potential movement artifacts.
—Use KCL or NaCL electrode gel as the conductive medium between electrode and the skin. Implement a 15-minute biosensor acclimation period for the skin-electrolyte interface to stabilize.
—Back up data after every session and delete files stored in the sensor
Synchronization
—Synchronize the sensor time with real-time before each treatment session
—Verbally narrate relevant events (e.g., sensor A is on the participant's right ankle and first flashed at 8:03:05 am)
—Use the event-mark button for relevant events (e.g., start and end of treatment sessions)
—After placing sensors on child and marking an event, move sensors back and forth in front of the camera to synchronize accelerometer and video data
—Use a visual analytic tool to visualize and synchronize the data (e.g., BEDA).
Data Preprocessing and Analysis
—Analyze both the phasic and tonic components of EDA (for deconvolution approach, see Benedek and Kaernbach 2010b)
—Use a visual analytic tool to assist with data preprocessing and analysis (e.g., BEDA)
—Normalization across subjects is needed for between-subject comparisons (e.g., Hernandez et al. [2014] normalized the range between 0–1)
Recommended Thresholds:
—Exclusion of SCRs if greater than 1.0μS (Dawson et al. [2000, 2007]; with Doberenz et al. [2011] recommending a .5μS threshold) as this likely represents movement artifacts or loose electrodes
—Exclusion of SC data if values are below .5μS [Doberenz et al. 2011] given the typical SCL range is between 2μs and 20μs (Dawson et al. [2000, 2007])
—Minimum amplitude threshold of .01μS although criterion is ultimately dependent on the resolution of the recording (Boucsein [1993, 2012], 156–157, Dawson et al. [2000, 2007], Hernandez et al. [2014])
—Minimum distance between NS.SCRs of 1 second [Hernandez et al. 2014]

throughout the study is advised. Ambient temperature is positively correlated with the frequency of SCRs between subjects [Doberenz et al. 2011; Turpin et al. 1983] and is significantly positively correlated with a variety of EDA measures within subjects [Doberenz et al. 2011] and EDA has been reported to be lowest in the morning [Miro et al. 2002]. Related to this, hydration of the skin (both endogenous and exogenous) may also influence EDA highlighting the importance of the medium of conduction used. Electrode gels containing either KCl or NaCl are recommended during short-term EDA assessment to avoid variations in EDA, and improve signal acquisition, as both of these appear as salts in the stratum corneum (readers are referred to Boucsein [1993, 2012], 117 for additional details). In order for the skin-electrolyte interface to stabilize, a biosensor acclimation period of approximately 10–15 minutes should be implemented.

Physical Activity. Physical activity may influence SC via thermoregulation. However, associations between motor movement within daily activities in humans and skin conductance is not yet well elucidated, especially in children. Turpin et al. [1983] assessed long-term ambulatory SC recorded from the fingers in a group of 12 adults, and found no between-subjects or mean within-subject significant correlations between arm movements and EDA. On the other hand, within-subject comparisons in a group of 48 healthy adults who wore ambulatory SC devices on their fingers for a 24-hour period, showed significant positive relationships between physical activity and EDA with the exception of amplitude of NS.SCRs, which decreased with increased physical activity [Doberenz et al. 2011]. As such, although corrections for the effects of confounding variables such as physical activity may not be necessary at the between subject level, corrections are recommended at the within subject level. For the SL-EDA study, even though physical activity was somewhat constant within subjects across sessions, physical activity such as walking, running, bouncing, jumping and/or engaging in repetitive motor mannerisms led to movement of the electrodes and/or to loose electrodes thereby increasing artifacts in the data. As previously discussed, securing the electrodes with medical tape or a wrist or ankle wrap is advised.

Individual Differences. Given that EDA may vary with differences in race, age, sex, body mass index, sweat gland density, and use of medications and psychoactive substances [Doberenz et al. 2011], controlling for such factors is advised and normalization across subjects is needed for between-subject comparisons (e.g., Hernandez et al. [2014] normalized the range of values to be between zero and one). For additional information regarding race/ethnicity differences in SC in particular, see Wesley and Maibach [2003]. For a detailed and broader review of the effects of and interactions with individual differences, see Boucsein [1993, 2012].

5.2.2. Sensor Functioning. Investigators are encouraged to collect data using two sensors (one on each side of the body) given potential EDA asymmetry [Picard et al. 2016], and to have at least one other sensor readily available to use for data collection in case one of the sensors malfunctions. The sensors should be calibrated to be the same, and data collected across the two sensors should be visually inspected. Given the challenges experienced with the Bluetooth device, we recommend to use the internal storage for data collection and analysis. Additionally, depending on specific protocol to follow (e.g., handwriting) or depending on participant (e.g., child's basal SC level is low), as long as data across sensors are comparable, whether data are analyzed for the dominant or non-dominant wrist/ankle may vary. If interested in yielding a higher amplitude, analyze data from the dominant wrist/ankle (see Román et al. [1989]). If interested in decreasing potential movement artifacts, analyze data from the non-dominant wrist/ankle. Finally, to avoid exceeding the threshold of directories stored in the device, we recommend backing up the data after every session and deleting the files in the sensor.

5.2.3. Synchronization. We would like to remind researchers to synchronize the internal sensor-time with real-time prior to the onset of each treatment session. Moreover, additional strategies to assist with synchronizing audio-video recorded data with physiological data include: (a) verbally narrate relevant events for the recording (e.g., "sensor 'A' is on the participant's right ankle and first flashed at 8:03:05 am"); (b) press the event-mark buttons on the sensors for relevant events (e.g., at the beginning and end of the sessions); and (c), after placing the sensors on the child and marking an event at the beginning and end of the session, move the sensor back and forth for a few seconds in front of the camera to synchronize the accelerometer data with the video data. The latter was the preferred synchronization strategy by the researchers. Finally, we advise

researchers to use a visual analytic tool to visualize, synchronize, and analyze the data such as BEDA.

5.2.4. Data Preprocessing and Analysis. Analyzing both the phasic and tonic components of EDA is recommended as these can aid in the interpretation of overall skin conductance results (without decomposition) and aid in the understanding of the physiological/neurological underpinnings of the various EDA measures. Researchers interested in exploring the deconvolution approach are referred to Benedek and Kaernbach [2010b]. Although future studies should address what the optimal thresholds for preprocessing and analysis of short-term *in situ* SC are in order to establish a recommended set of thresholds, based on the current literature the following are recommended: (a) exclusion of SCRs if greater than 1.0uS [Dawson et al. 2000, 2007], with Doberenz et al. [2011] recommending a .5uS threshold) as this likely represents movement artifacts or loose electrodes, b) exclusion of SC data if values are below .5uS [Doberenz et al. 2011] given the typical SCL range is between 2uS and 20uS [Dawson et al. 2000, 2007], (c) a minimum amplitude threshold of .01 although criterion is ultimately dependent on the resolution of the recording [Boucsein 1993, 2012], 156–157, Dawson et al. [2000, 2007], Hernandez et al. [2014], and (d) a minimum distance between NS.SCRs of 1 second [Hernandez et al. 2014].

6. CONCLUSIONS AND FUTURE DIRECTIONS

Skin conductance has largely been monitored in highly controlled experimental conditions and more recently has been successfully monitored *in situ* in individuals with generalized tonic-clonic seizures who present with significantly larger and more frequent skin conductance responses, but less so to monitor more general variation during daily activities. The present work is novel in presenting behavioral and technical methodological considerations, derived from novel *post hoc* analyses, when monitoring EDA in children with neurodevelopmental communication impairments based on the results of two studies examining continuous short-term EDA *in situ* during speech-language and occupational therapy.

The SL-EDA study monitored skin conductance in children at the single-word developmental stage undergoing speech-language treatment to increase their multisyllabic productions and examined associations between skin conductance and emotional valence. The OT-EDA study monitored skin conductance in children with sensory processing difficulties undergoing occupational therapy and examined associations between skin conductance, use of a pressure vest, type of instruction, academic engagement and challenging behaviors. Younger children (ages 2–4) wore the sensors for approximately 62% of the sessions, whereas older children (ages 9 and 11) wore the sensors for all of the sessions. Unfortunately, due to a combination of behavioral and technical challenges a large percentage of data were discarded (i.e., 29%) and is often discarded when monitoring EDA in children and/or in applied settings (e.g., 31% of the data were discarded in Hernandez et al. [2014], and 54% in Miller et al. [2007]). We presented behavioral and technical considerations including the use of desensitization techniques and recommended thresholds based on the current literature for preprocessing and analysis of EDA data.

Moving forward, research should focus in how to improve signal acquisition, due to both behavioral and technical challenges, to decrease overall percentage of data being discarded, on how to simplify the process of synchronization across multiple data sources within the field of accessible computing, and on establishing a set of recommended thresholds for acquisition of short term *in situ* SC data. In sum, although the present work shows it is feasible to record EDA *in situ,* it highlights many of the challenges of monitoring EDA in applied settings, or in other words in uncontrolled

environments. It is of particular importance that we recognize and address these challenges before commercializing the use of biosensors that measure SC to children with neurodevelopmental communication impairments. Ultimately, we aim to aid in the development and improvement of automated noninvasive unobtrusive and easy to interpret tools for measuring levels of emotional arousal via skin conductance, the only noninvasive autonomic nervous system measure innervated solely by and consequently most representative of sympathetic nervous system activity. Although not yet ready to be adopted within clinical practice or within the homes of children with neurodevelopmental communication impairments, EDA technological advances offer a unique opportunity to assess changes in emotional arousal that may help guide teaching opportunities for children with neurodevelopmental communication impairments.

ELECTRONIC APPENDIX

See online appendix included in the ACM Digital Library to view a social story akin to that used as a desensitization strategy during the SL-EDA study.

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