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SUPPORTING SELF-REGULATION WITH DEFORMABLE CONTROLLERS

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by

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Abstract

Supporting Self-Regulation with Deformable Controllers

by Peter S. Cottrell

This body of work develops deformable controllers that serve target populations in self-regulation techniques. Two key projects are described, with several iterations of each developed using Research-through-Design methods. The controllers were created using off-the-shelf materials as a basis for shared development between research groups. The first project presented is the development of an anthropomorphic creature, in the tradition of Socially Assistive Robotics, designed to scaffold children's emotional self regulation through an intimate-space interaction (taking place with the object held close to the body). I describe the project from brainstorming to iteration to deployment, as well as knowledge transfer to a private company for deployment and some of their findings. The second project described is a deformable controller in the form of a ball that can be used to track fidgeting differences and focus intervention, between neuro-typical and ADHD users. Both these projects were developed as part of multidisciplinary teams with members at and beyond UCSC. The development and deployment of these devices extends research insights about the benefits of deformable controllers that leverage granular repetitive interactions to provide practical and expressive value to end users, while providing a research platform for further investigation into personalized interaction.

Thank you to my Family, Friends, Cohort and Partner that helped me stay sane and focused.

Acknowledgements

The text of this dissertation includes material from the following publications: Soft-Bodied Fidget Toys: A Materials Exploration, [3], "I Just Let Him Cry...: Designing Socio-Technical Interventions in Families to Prevent Mental Health Disorders", [4], and Translating Affective Touch into Text, [5], with additional material from the in-review journal article Design not Lost in Translation: A Case Study of an Intimate-Space Socially Assistive Robot for Emotion Regulation, [6]. The co-author listed in this publication directed and supervised the research which forms the basis for the dissertation.

Chapter 1

Introduction and Motivation

This dissertation describes the exploration and development of two projects for field deployment that developed out of interdisciplinary teams, the Social and Emotional Learning (SEL) Animal and the Fidget Ball. Both projects try to bridge key gaps in the market for naturalistic data collection devices. The SEL Animals focus on usage with children to help teach healthy SEL techniques through a deformable robot, an electronics embedded plush creature with data collection as well as feedback to the user for focused intervention. The Fidget Ball uses the same core electronics embedded across the surface of a flexible controller that currently acts as a data collection device for studying the fidgeting habits of those with ADHD. While Machine Learning has not been integrated into the current projects, both devices were designed to collect data that could be leveraged for ML purposes. In the long run, this could mean that the devices could support data-driven feedback loops and opportunities for analysis of use patterns to support tailored interventions.

These deformable devices are intended to largely retain their shape using flexible structures but conform to a user's touch when pressure is applied, and use electronics embedded within to record and react to the user's interaction. The devices are designed to invite habitual, repetitive, sometimes unconscious touch patterns (sometimes referred to as fidgeting) that prior research indicates supports emotional and cognitive regulation [7, 8]. Devices that are able to capture natural behavior allow researchers to develop a rich set of data that can support interventions to help support self-regulation.

Within this dissertation I attempt to answer 3 research questions:

1 Can we design a touch-based intervention tool that supports self-regulation?

2 It is possible to detect a person's attentional or emotional state via their interaction with a tangible interface?

3 Can we provide timely feedback that further helps the individual self-regulate?

I'll examine these research questions for each project, reframing them with slightly more specific lenses.

Projects like these are interdisciplinary, with multiple researchers needed to make any one project possible. While I will be framing each section and highlighting my personal contribution (primarily the construction of the devices), there will be description of influences and findings from external collaborators, namely crafting experts like April Grow and Ella Degan, psychologists and field researchers like Petr Slovak and Nikki Theofanopoulou, machine learning experts like Daniel Shapiro, and most recently Julie Schweitzer's team of ADHD researchers at UC Davis. All of this research has been under the advisement and supervision of Katherine Isbister. We as a research team look to fill a research gap within the fields of SAR and deformable controllers by developing research platforms for repetitive behavior observation.

Chapter 2

Literature Review

In this section of the dissertation, I review research literature that situates the projects. First, I'll review research into fidgeting and how that might be linked to therapeutic effects. Second, I'll cover Socially Assistive Robotics as it relates to behavior modification. Finally, I'll review smart materials and haptic response, including emergent efforts of the Maker community.

2.1 Therapeutic Work in Touch and Fidgeting

We use touch everyday to influence and be in tune with our surroundings, so it makes sense that we are particular when it comes to texture, materiality and tactile response from the things we touch. We react both consciously and subconsciously to touch stimuli, for example when stroking or petting an animal our bodies react with short-term reductions in blood pressure and heart rate [9–11].

One particular case of touch interaction is fidgeting. This behavior occurs naturally in children and adults alike. There are a range of social/cultural responses to fidgeting behavior, depending on factors such as local norms, task presented to the fidgeter, and object used for fidgeting [8, 12–15]. To better understand desirable material properties in fidgeting devices, Karlesky collected self-reports of fidget object choices and behaviors via the online forum Tumblr, and found users referenced "self-regulation effects including calm, focus, creativity, and optimal arousal" as reasons for using their preferred devices [7]. Full-body fidgeting in ADHD patients seems to help compensate for low arousal levels and to increase attention levels, according to early findings from Schweitzer's research group [16].

The scientific exploration of our inclination to fidgeting for concentration has just begun, and still needs more through exploration, but despite a lack of robust empirical support, the market of objects that have been developed to take advantage of therapeutic touch and fidgeting is growing. For example, the use of live therapy pets/animals is popular in universities, care homes and offices to help regulate stress levels in the population, although health concerns are raised when animals are brought into public spaces because of pet dander, risk of aggression, or other discomforts with live animals in enclosed areas.

An alternative means of animal-human therapeutic touch has been evolving, using technology to supplement live animals under the banner of Socially Assistive Robots (SAR) [17].

2.2 Socially Assistive Robotics

As an artifact of an increasing ratio of elderly adults in comparison to their young caretakers in Japan, there is a drive in Japan's public research efforts to develop robots that help stimulate wellbeing and healthy behaviors. As a result the Socially Assistive Robotics (SAR) [18] field has focused primarily on companionship for older people in nursing homes. Paro [19] and Aibo [20] are two well-known early examples of such robots, although a variety of other creatures have been developed in the intervening period. Hutson, et al.'s review of the suitability of SARs for the wellbeing of the elderly found that most participants were unsatisfied with their social robots [2]. Many of these robots are some variety of animatronic puppet that are a pliable rigid skeleton covered by soft faux fur and use either voice commands, computer vision or limited physical inputs to detect human interaction. To help make the SAR plush around the skeletal structure, most are either table-bound [21–25], oversized (in the case of CuDDler, weighing in at 4 kg) [26], or do not have a plush exterior [19, 20, 27–31]. Hutson et al. noticed a disillusionment with the metaphor after a short period of working with animal-based SARs, and proposed that perhaps they were too analogous to house pets and therefore directly in competition with expectations of a living creature–such that this high expectation bar resulted in the SAR being evaluated as "not sufficiently lifelike" [2].

To alleviate this issue, some groups have taken a more limited and abstract approach to supportive SARs, for example a haptic "breathing" robotic creature that only tries to regulate breathing rate in the user, through vibrations in response to petting [27, 28]. In implementing these more limited and abstracted creatures that still evoke caring behavior, it is perhaps possible to create a relationship between user and creature that helps encourage the user's self reflection upon their own self regulation (aiming one's emotions and physiological state toward an optimal, relaxed, alert condition). There have also been commercial ventures into abstract creatures, like the ever evolving Furby or more recent creatures like the Qoobo, a pillow with a wagging cat tail that reacts to touch [32]. In table 2.1 I characterize notable social robots considering key factors of main focus, type, material, audience, emotional expression, and modality (speech, touch, light, sound, movement).

Robot Name	Main Focus	Type	Material	Target	Emotions	User Input	Behavior
Aibo	E	Aml (dog)	P	A	Y	T,So,Si,Sp	Sp,So,Mo
CareBot	H	Rbt	P	All	N	Si,Sp	L,Sp,Mo
Companion-Able	C	Rbt	P	E	Y	T,Sp,Si	L,Mo,Sp
FurReal Cat	E	Aml (cat)	F	C	Y	T	So,Mo
Hasbro I-Cat	E	Dvt (cat)	P	A	Y	T,So	L,Mo,So
Heart Robot	C	Hmd	C	All	Y	T	L,Mo
Homie	C	Aml (dog)	F	E	Y	Sp,T	L,Sp,So
Hopis	H	Aml (dog)	C	All	N	/	Sp
Huggable	C	Aml (bear)	F	C	Y	T,So,Si	Sp
iCat	C	Aml (cat)	P	All	Y	T,Sp	L,Sp,Mo
KASPAR	H	Hmd	R	D,C	Y	T,So,Si,Mo,S	Mo
Keepon	H	Dvt(snowman)	R	C	Y	So,Si	Mo
Mood Lamp	E	Dvt (mushroom)	P	C	Y	T,So	L,So
Nabaztag	T	Dvt (rabbit)	P	A	Y	Sp	L,Sp,Mo,So
NeCoRo	C	Aml (cat)	F	All	Y	T,So,Si	So,L
Nursebot	H	Rbt	P	E	Y	T,Sp,Si	L,Mo,Sp
Paro	C	Aml (seal)	F	All	Y	T,So,Si,Sp	So,Mo

Robot Name	Main Focus	Type	Material	Target	Emotions	User Input	Behavior
PC Mascot	T	Dvt (parrot)	P	A	N	/	L,Sp,Mo
Pleo	C	Aml (dinosaur)	R	All	Y	T,So,Si	So,Mo
Probo	C	Aml (elephant)	C	C	Y	T,So,Si,Sp	L,Mo,Sp
Robosapien	E	Hmd	P	C	N	T	Sp
Teddy Phone	T	Dvt (bear)	F	A	N	So	So,Mo
USB Robot Owl	E	Dvt (owl)	P	A	N	/	Mo
Wakamaru-bot	C	Hmd	P	E,D	Y	Si,Sp	Sp
Yorisoi Ifbot	C	Hmd	P	E	Y	Sp	L,Sp,Mo

Table 2.1: Main Features of Notable Social Robots (See below for table key)[2].

Key	
Main Focus	H:healthcare,C:companion,E:entertainment,T:communication
Type	Aml:animal,Hmd:humanoid,Rbt:robot,Dvt:device-type
Material	C:cloth,P:plastic,F:fur,R:rubber
Audience	All:all ages,E:elderly,D:disabled,A:adults,C:children
Emotions	Y:yes, emotions are expressed,N:No expressions
Modality	Sp:speech,T:touch,L:light,Si:sight,So:sound,Mo:movement

2.3 Smart Materials and Haptic Response

As different groups developed their SARs it's clear that each carries a strong identity through it's material qualities. We each have inherent and immediate reactions to material qualities, something well-known to product designers. In my research, in particular with the emotion regulation SAR, I was interested in using haptic feedback to the end user. I found that the scientific and empirical documentation of interpretive facets of haptics (how they will feel to end users) are not yet well described by engineers who have created haptic motors and systems. Communicating through vibration and texture draws upon a complex vocabulary that can be variable between one application and the next, and change within local conventions. For example, phone users' response to vibration patterns has evolved with the rapid deployment of mobile phone technology. We can leverage this familiarity to help build a metaphor of physiological/biological vibration of an SAR that can then influence the end user [27, 28, 33].

In parallel to the development of a shared vocabulary in haptics, the growing community of open source hobby builders, or Makers, has encouraged the rapid growth of prototyping material suppliers like Arduino and Adafruit, providing access to previously hard to access materials to a larger community. Groups working with smart materials such as conductive fabrics, electronic textiles (e-textiles), micro-controllers, piezo-restive plastics and memory alloys have been exposed to a broader, consumer market, and as a result it becomes more possible to create interesting deformable controllers such as those created by Mika Satomi and Hannah Perner-Wilson in their collective Kobakant [34, 35].

In my dissertation work, I took advantage of the broad range of available DIY materials and designs to prototype surfaces and materials that lend themselves to naturalistic data collection through deformable controllers. Lessons learned from this work can, I believe, feed back into this community as they evolve new interaction paradigms and prototypes.

2.4 Opportunity Space

My literature review revealed some important gaps. Though there has been research concerning fidgeting to support attention regulation, no one had yet created a smart fidget device with the appropriate affordances that could track touch traces. In addition, my review of the SAR literature showed that there might be an opportunity to focus closely on a simplified (and thus potentially lower cost) emotion regulation SAR that made use of haptic feedback. I also saw opportunity to build touch trace tracking into this class of devices, to enable future ML analysis of touch traces toward tailored interventions to aid in both attention and emotion self regulation.

Chapter 3

Methodology and Contribution

3.1 Research through Design

To conduct the research described in this dissertation, I used a Research through Design (RTD) approach. This set of research practices developed from the key insight that the act of designing and building leads to research insights and contributions. RTD practitioners aim for 'possible' futures, engaging in design activities to shape artifacts and interactions that can help to deliver those futures [36]. RTD is a rigorous form of design practice that is well-suited to the problem spaces that I and the interdisciplinary research teams I was working with wanted to explore. It involves articulating a problem space, and working in an iterative fashion to develop prototypes that help to meet the needs of the problem space. In my case, the design space was the creation of deformable controller objects that could afford and encourage self-regulator touch behaviors. I worked closely on both projects with subject-matter experts who could help to drive the design choices along the way, with the end goal of testing out the devices with the target populations. The end result of RTD is both artifacts and design knowledge that can be extrapolated from those artifacts. In my case, artifacts and design knowledge (in particular the intimate space robot concept I'll describe later) were key results.

3.2 Contribution and Collaborators

The work described in this dissertation could not have been done without a talented team of people at multiple institutions. I worked with crafting experts like April Grow and Ella Degan, psychologists and field researchers like Petr Slovak and Nikki Theofanopoulou, machine learning experts like Daniel Shapiro, and most recently Julie Schweitzer's team of ADHD researchers at UC Davis on an NIH grant using the fidget ball to ask basic research questions about whether fidget objects can help those with ADHD manage their attention. All of this research has been under the advisement and supervision of Katherine Isbister.

My primary role on both projects was lead engineer. As such, I drove the design, implementation, and maintenance of software and hardware of the devices. I worked closely with the craft designers to co-develop the surface features of the devices in ways that were compatible with the underlying sensing strategies. Once the devices were built, I was involved in pilot testing (including verifying data analysis cohesion) of the Fidget Ball. I also worked to adapt that user study to support the NIH-funded study at UC Davis. I supported our SEL creatures during user testing, maintaining the device multiples and collecting and analyzing the touch trace data they collected for our publications about that work. I also helped with translation of our designs so that a commercial partner could build a device based on our research.

Chapter 4

Designing Creatures for Social and Emotional Learning

4.1 Purpose

This project was developed with inspiration from Michael Karlesky's investigation into fidget objects and their design parameters [37], which described a wide range of textures and shapes users preferred in an exploration of situational fidgeting. We wanted to expand that work by exploring what materials could lend themselves to those textures, while supporting the collection of touch traces to provide researchers with data to know what happened in-situ. We then used the results of these basic explorations in collaboration with our partner Petr Slovak from the University of London. He was hoping to help create an object to scaffold Social and Emotional Learning (SEL) skills in children (8-12 years old). In this section, I will describe the research and development trajectory for this project. The research questions for this project were:

1 Can we design an intervention tool that helps scaffold children's emotional regulation through touch-based interactions?

2 It is possible to detect a person's emotional state via their interaction with a tangible interface?

3 Can we provide timely feedback from the device that helps the individual self-regulate?

Material from this chapter has been published in the proceedings of TEI 2018 [38], CSCW 2018 [4], is in review as a ToCHI Journal article [6] and was the basis for a JMIR 2019 Journal article [39].

4.2 Blue Bean Animals: Materials Exploration

The first step in the research was an RTD-style 'smart' materials exploration. Karlesky [7] collected sample fidget object images/videos and associated descriptions, and used those to compile a list of features for their properties:

> *crinkly, squishy, squash, snap, hissing, strumming, clicky-clackety, cool, smooth, rough, mush, twirl, spin, roll, bounce, shaking, braid, flipping, clicking, scrunch, squeeze, rub, and twiddle*

Examining the objects and descriptors from this study shows that fidgeters seek a combination of complex sensations in fidget items, many of which are not present in current electronic tangible devices [13].

Building from this work, I collaborated with April Grow, Ph.D., as a crafting and sculpting designer, bringing my own knowledge of hardware and mechatronic design. Together, we set out to develop prototypes that encompassed as many of these sensations as possible, which could also capture touch traces unobtrusively. The work started in the summer of 2016 focusing on brainstorming and material exploration and continued into the first part of 2017 constructing exemplar animals, Figure 4.1. A large portion of this section was published and presented in the TEI 2018 proceedings [38].

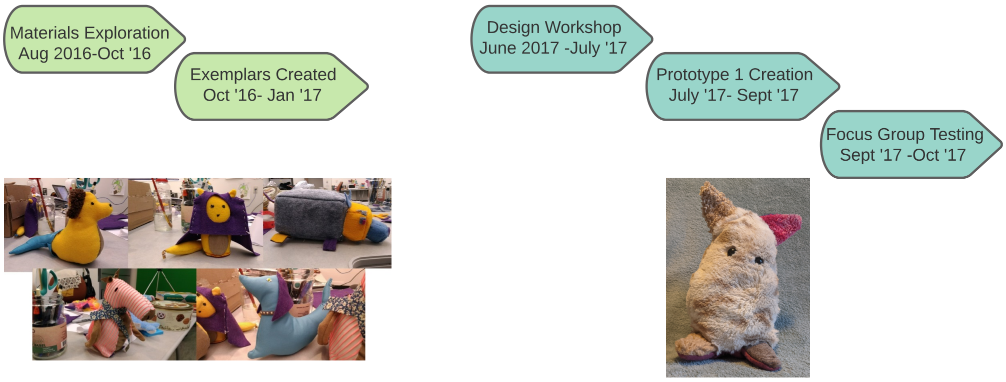


FIGURE 4.1: Timeline between August 2016 to October 2017, BlueBean project indicated in light green, followed by first iteration of the Anxious Creature in dark green.

4.2.1 Brainstorming and Sketching

These explorations were shaped by an emerging partnership with Peter Slovak, and with Committee for Children, a non-profit that supports teaching Social-Emotional Learning (SEL) to children. CfC was interested in whether we could develop smart fidget objects to support building these skills–for example self-regulation. We decided to focus our design efforts on crafting objects that could potentially appeal to children ages 8-10.

We gathered two sets of materials, those that mimicked or had some traceable properties, and those that would form the infrastructure around which the smart material could be integrated. Notable materials included in our collection:

- 2 varieties of conductive fabric, MedTex180 (a soft cotton-like variant) and RipStop (analogous to a stiff starch pressed shirt)
- Faux Leather to imitate Eeonyx non-woven resistive fabric
- Pressure sensors - made of Velostat and conductive tape
- Squeeze sensor - knitted yarn balls with interwoven conducive tread

After gathering a sampling of materials, Figure 4.2, we sketched out ideas that would make for interesting repetitive use interactions, drawing from fidgeting actions as described in our criteria. We envisioned a unique interaction for each word from Karlesky's list, with some basis in traceable data. Some examples include: "squash" a ball sensor to determine grip strength, "strumming" a field of flex sensor embedded grass, "rub" the belly of a creature with embedded conductive thread strands.

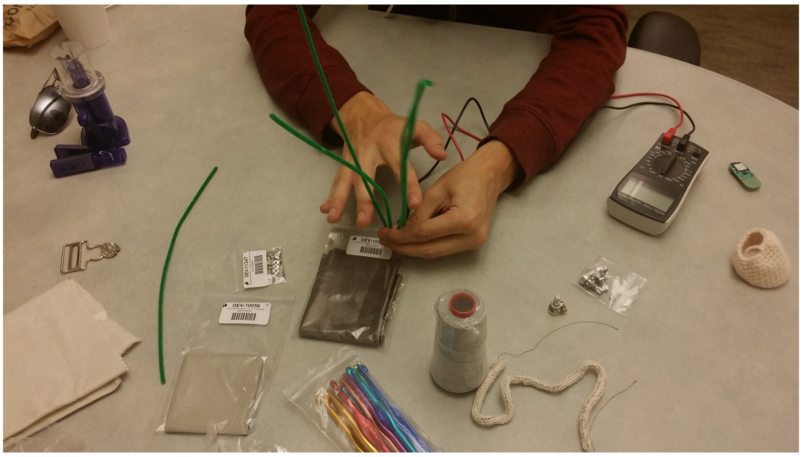


FIGURE 4.2: Early materials exploration and brain storming

By the end of our brainstorming we had a set of ideas that blended different fidget qualities and materials, including a potted plant that had bunny ears instead of leaves, which would light the pot up when the ears were squished or played with; a hedgehog that would flex its spines when threatened and relax when its belly was rubbed; and a set of conductive scales that would understand when the creature was being reshaped (Figure 4.3). We consolidated and integrated the various designs, and settled on two main fidget-able plush toys that would incorporate most of our favored sensors — a hedgehog and a dragon.

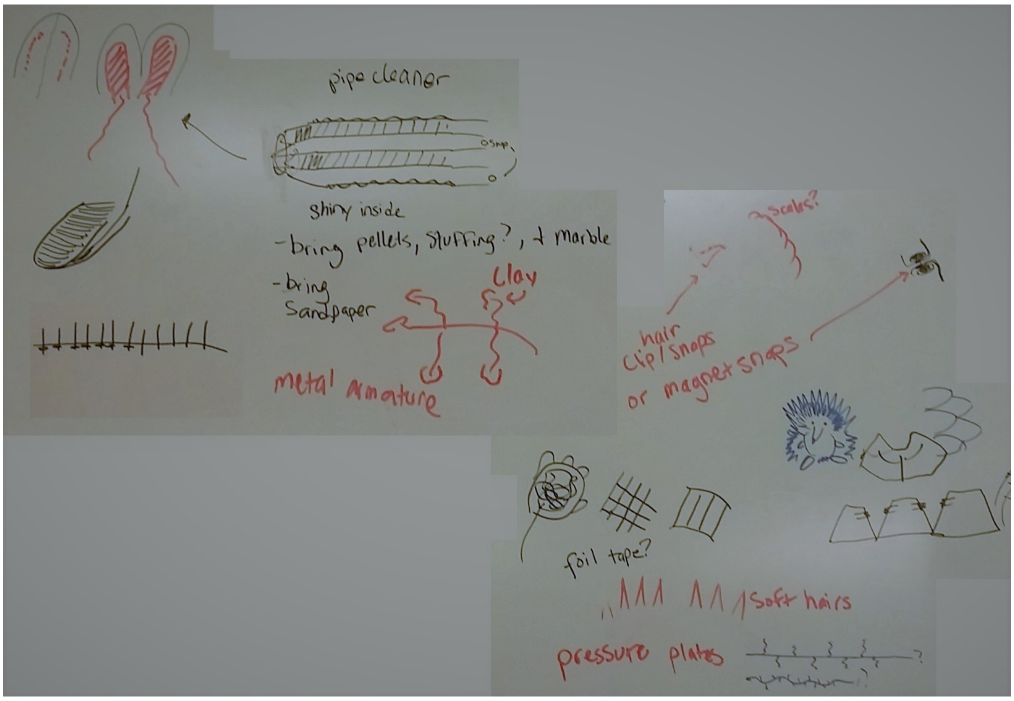


FIGURE 4.3: Sample of sketches during workshop, upper left an idea for using pipe cleaners and stuffing to create a pressure sensor in the style of rabbit ears. Lower left walks through using copper tape and magnets as connectors, and using ideas from soft-robotic designs to create a folding sensor.

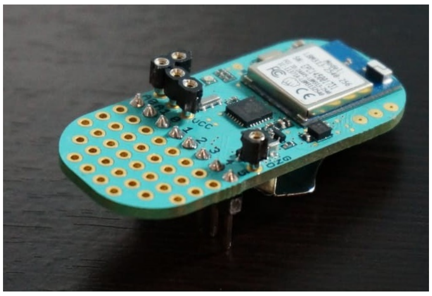


FIGURE 4.4: LightBlue Bean Microcontroller

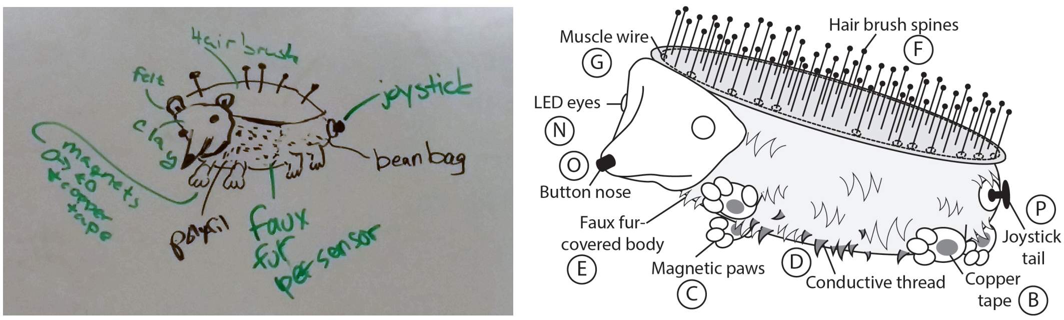
A key priority we had while designing for children, was to keep them safe by reducing external wires, and keeping the objects small to fit comfortably in their hands. To reduce the size, the interior hardware must remain small. We evaluated then current market-ready micro-controllers with the smallest possible footprint, and found a micro-controller that could communicate wirelessly and was powered by an on-board battery that could last for multiple days.

The LightBlue Bean from PunchThrough (see Figure 4.4) is 3 inches long, and has onboard Bluetooth, protoboard and battery. Its size ensures that it is less likely to be crushed or injured when placed within a soft structured object that will be manipulated/fidgeted with. It has 2 analog channels (capable of reading in a range of values from a sensor) and 6 digital channels (capable of detecting if a switch is open or closed), which means we needed to be strategic about how many and what style of sensors we tried to integrate into a single design.

An advantage of the reduced array of sensors was that it allowed us to get an extended battery life, allowing for minimal down time. Unfortunately, the

LightBlue Bean uses single-use coin cell batteries rather than the more popular rechargeable lithium batteries, but with the Low-Energy Bluetooth protocols the battery lasts for multiple days of interactions before losing power. Programming was done in a mix of Arduino and Blue-Bean-specific coding.

4.2.2 Hedgehog



(A) Initial sketch of the hedgehog design (B) Final call-out diagram

FIGURE 4.5: Hedgehog design diagram iterations

Figure 4.5 is an illustration of the hedgehog's features, see Figure 4.8 for photo of final prototype. Our keystone sensors for the hedgehog were a pressure sensitive squeeze ball to elicit a stress ball fidget element, and a prickly sheet of pins that could detect when a user is stroking it to encourage 'strumming' or 'rubbing'. To keep our toy safe for use by children, we replaced the prickly pin sheet with a child-friendly metal-spined hairbrush with plastic nubs on the tips. It still elicited the same fidgeting textures, and was more durable than in-house built devices. The manufactured hairbrush embedded the metal spines in rubber and created limited metal contact between tines even under heavy twisting, so it turned out to be good for fidgeting, but difficult to create a conductive touch sensor field, as we had first envisioned.

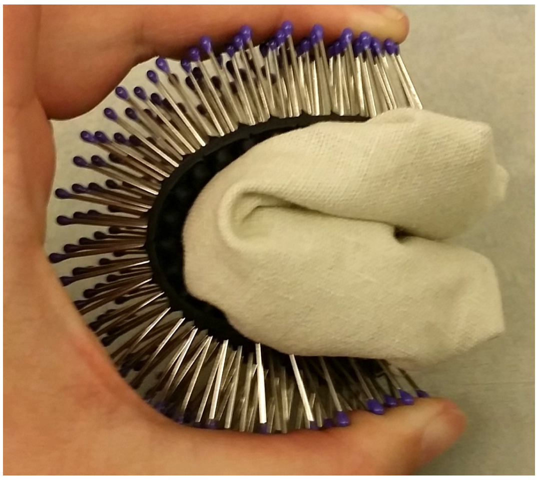
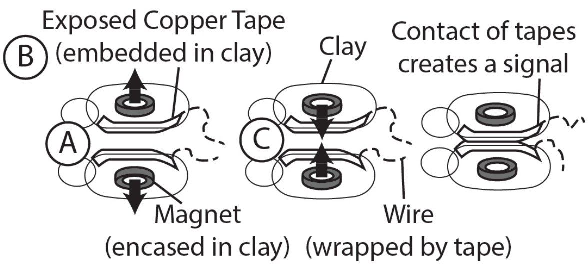


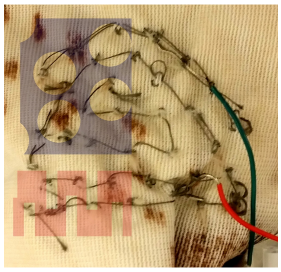
FIGURE 4.6: Early version of keystone modality of the Hedgehog.

As we built, we decided to remove the second keystone sensor (the pressure ball facet of the creature) for two reasons: 1) to keep healthy internal wiring, and 2) during our research through design testing, we found very few instances of heavy squeezing with the anthropomorphic values ascribed toward a small creature. We did keep the plush interior to invite some light 'squeezing' and to maintain the hedgehog characterizations ascribed to it.

We added LED eyes for feedback to interaction, a push-button nose for 'clicking', a joystick tail for 'rolling' under the thumb, and a field of conductive threads embedded into faux fur to detect 'petting' actions. The conductive thread is embroidered in two distinct sections; when the reverse side of exposed conductive thread is stroked the conductive fibers flatten and create a loose connection, detectable by the Blue Bean. This design is a carry-over from the original design planned for the metal pin field, seen in Figure 4.7b.



(A) Diagram describing magnets and copper tape embedded in clay to create 'clicky' and 'floating' feeling appendages



(B) Belly pet sensor, two discreet sections of conductive thread- indicated using blue dots and red waves

FIGURE 4.7: Diagrams showing detail of 2 sensor designs

While sculpting the paws for the creature, we observed salient textures in clicking two pieces of clay together, and wanted a way to detect when a user was 'clapping' the paws of the creature together. We ended up entombing magnets within the clay, and partially embedding copper tape hooked to an exterior wire to form paired surfaces that, depending on which direction the magnets faced, would either attract or repulse. With the exposed copper tape and paired magnets, a detectable connection for the microcontroller is created when paws meet, seen in Figure 4.7a.

To accentuate the anthropomorphic nature of the creature, we looked at creating additional feedback to the user in addition to the LED eyes. Attempting to create this capability, we added a ring of muscle wire around the perimeter of the hairbrush, which would allow flexing to imitate 'raised hackles'. However, when testing we realized the muscle wire either didn't have the leverage on the brim of the hairbrush or lacked the physical strength to stress the brush back to create the desired feedback. In future iterations of a similar prototype this design feature could be explored for better results.

(A) Front of hedgehog, the button-nose, LED eyes, flexible hairbrush back are visible

(B) Underside of the hedgehog, conductive clay paws and conductive pet sensor belly are visible

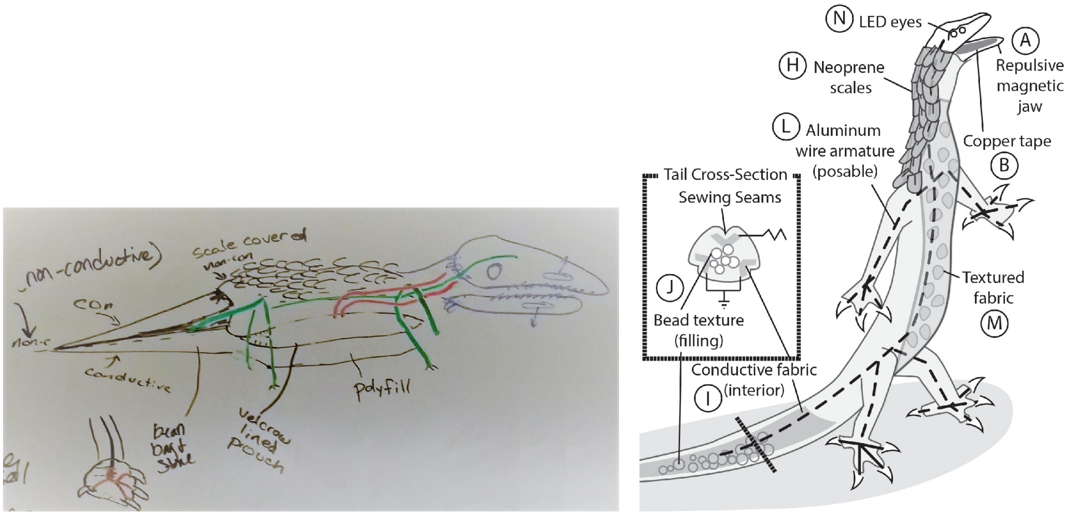
FIGURE 4.8: Final hedgehog design

4.2.3 Dragon

FIGURE 4.9: Fully implemented dragon design

Figure 4.9 is a photo of the final prototype, see Figure 4.10 for an illustration of the dragon's features. The initial concept for the dragon revolved around a sheet of conductive scales that could detect when the scales shifted position, and a conductive-fabric-lined squeezable tail filled with a variety of beads and stones to create a smooth texture within the tail.

The sheet of conductive scales and other sensors were heavily influenced by Mika Satomi and Hannah Perner-Wilson as detailed on their Kobakant collaboration website [35]. A key factor in creating the scale sensor is a neoprene style non-woven conductive textile called Eeonyx. Lacking a reliable distributor of Eeonyx resistive fabric, we substituted faux leather in anticipation that given positive response from user testing toward that component we could re-investigate sourcing the material. We wanted to create a cowl around the neck of the creature in the style of a bearded dragon.



(A) Initial sketch of the dragon design (B) Final detailed diagram

FIGURE 4.10: Dragon design sketches

The conductive tail was the single keystone that maintained its initial intent in either the dragon or hedgehog from brainstorming to implementation (see Figure 4.10b). To imitate the gangly nature of a reptile, we started with an aluminum frame around which we could layer different fabrics. We draped scales around the shoulders of the dragon, and found scale-textured faux fur that complemented the shoulder scales and used that for the underbelly. We also implemented several similar sensors to those in the hedgehog; repellent magnet pairs in the jaw to create a floating mouth, clay claws and LED eyes. While baking the clay to set its shape, the first set of LED eyes got overheated and died. Rather than resculpting the head, we mounted a second set using quick-set clay and used the second set to interact with the user.

For the weighted squeeze sensor that acted as a tail, we lined two pieces of conductive fabric along the top and bottom of the tail and filled the sleeve with poly-fill beads, rice and marbles. As the filler material inside the tail are moved aside, the two conductive pieces of fabric meet and create a circuit. This allow the micro-controller to detect approximately how much pressure the tail is being crushed with due to corresponding variable resistor values.

4.2.4 Summary of BlueBean Animals

After building the creatures, we found that what were perceived as unique implementations of sensors could ultimately be collapsed down into similar hardware design, but that we attained different perception of the hardware based on the contextualization. For instance, the embedded magnets provided different experiential properties depending on if the magnets attracted or repulsed each other and where in the creature they were placed. The conductive threads to detect petting were analogous to the original plan for spine flexion in the hedgehog's back.

After extended use, we did notice that many minor features in the sensors failed, for example the conductive thread got tangled in the mid-length pile faux fur and ultimately recorded nothing in the conductive pet sensor. We also found that while the wireless capabilities made the toys easy to program on the fly, we still needed to be able to access the controller boards for repairs or for replacing batteries. In the dragon this was relatively simple, but the hedgehog's board was in the exact center of the creature, so its board had to be sewn inside each time we wanted to present the creature.

As part of a larger study on fidgeting in children by Suzanne da Câmara, presented at DIS 2018 [8], the two animals were presented for a short period during focus groups with children. The observational data on how children related to the creatures showed that each individual toy held the interest of a smattering of participants and while the hedgehog was generally interacted with more, neither toy could hold broad interest in all participants due to preconceived notions of the base animals. That is to say one child might like dragons while another preferred a monkey to either a dragon or a hedgehog ,and thus was uninterested in the creatures we had developed. We intended the creatures as 'sampler' objects showcasing various sensor features, but this information proved valuable in the next phase of the research.

4.3 Second Exploration: Companion Creature

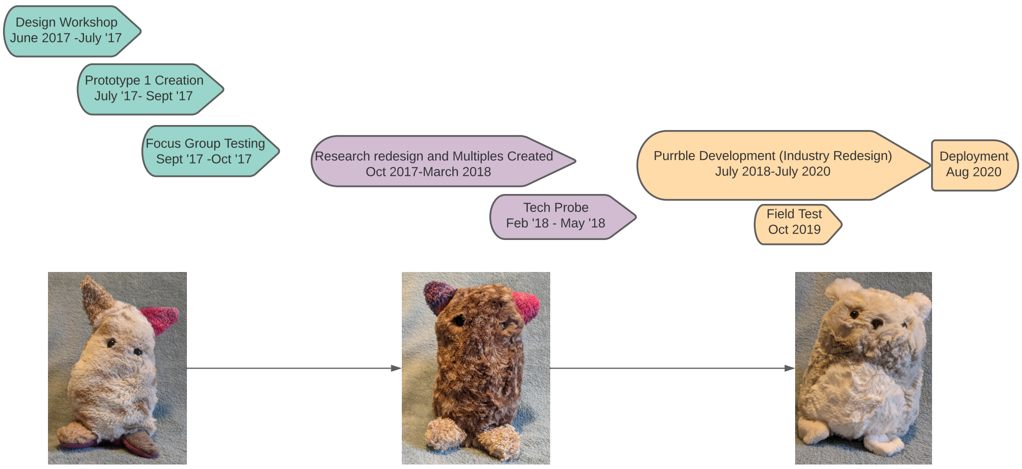


FIGURE 4.11: Timeline of the SEL creature development, early prototyping in green, upscaling in purple and external translation in yellow.

We were able to leverage lessons learned from building the BlueBean animals, in this interdisciplinary project aimed at creating an aid for self-regulation in children. Alongside collaborators from CfC and Petr Slovak, a Visiting Research Fellow at UCLIC, the team drew upon extensive prior interviews with parents and children about their emotion regulation strategies and family communication about emotion regulation [4] to develop an overall approach for the kind of intervention that we wanted to scaffold with the device: 1) the device would be a 'situated intervention' allowing children to practice regulation in the moment in everyday life, and 2) the intervention would be child-led rather than parent driven.

The research team set out to craft a device specifically for children (focusing on elementary school age as a crucial target for preventative interventions, cf., [4] for details), which offered the child an opportunity to engage in specific fidgeting interactions, toward scaffolding their own self-soothing and emotional regulation practice.

In the field observation of fidgeting behaviors [8], children were asked to imagine and explain their own ideal fidget devices. Many of the children produced sketches of creature-like fidgets, with eyes, limbs, and furry surfaces. We realized that children were very familiar with hands-on play with toys that had animal-like properties, and that this helped to set a familiar social frame for interacting with the toys. At this early moment in the design process, we decided to leverage the social expectations for interaction that would go along with framing the fidget device as a creature. This led us to specify a role for the device, and to develop it as a socially assistive 'robot' tangible. The role we selected was a small, vulnerable creature (not unlike the child) but also, with the potential to develop coping strategies (like the child). The creature would have an ambiguous identity and backstory that could allow projection by the child onto the robot. This could facilitate the child to rehearse coping strategies under the guise of caregiving. In this we drew upon prior research showing the therapeutic benefits of interaction with creatures that are vulnerable and smaller than oneself (such as pets–see [27] and [40]), and the benefits of role-play as a path toward self-efficacy and empowerment in situations a person perceives as difficult or scary [41]. We also drew upon research exploring the benefits of strategically deployed vulnerability in technology design [42], and on the use of ambiguity in design to allow for user projection and meaning making [43].

Thus the intended core logic of interaction with the device would be that the child would be able to sense that the creature was anxious, and would be able to use (self-soothing) fidget behaviors to calm it, leading the child to engage in emotion regulation strategies well known to psychology researchers of *attention redeployment* (from their own feelings/troubles to those of the creature) and *response modulation* (engaging in self-soothing fidget behaviors under the guise of caring for the creature [4]) – see [39] for a detailed description of the underlying intervention theory of change.

Our intent was to create an interactive device (now framed as a socially assistive robot) that used a particular role (vulnerable, small creature) to evoke self-soothing behaviors in the form of care-taking the creature. Guiding design concepts we brought to this process were allowing for **ambiguity**[43] in the design, to allow children to project their own concerns and stories onto the device; and evoking **vulnerability**[42, 44] to encourage care-taking and long-term engagement. We also intended to design the creature so that it could be seen as having the **potential to develop coping skills**. The device also needed to afford appropriately **self-soothing tactile interactions**.

After identifying interesting design interactions, our team developed preliminary prototypes to internally test and rework design parameters. Next, the refined prototype was shown to a focus group of children who provided qualitative feedback about the device. The design team used this feedback to modify the prototype, and created multiples of the revised device to deploy in an 'in the wild' technology probe with families.

The work-shopping phase started in June 2017 and pilot results of the longitudinal study were gathered in March of 2018, followed by translation by a private company for full market deployment in Aug of 2020, for a full break down see Figure 4.11.

4.3.1 Contribution

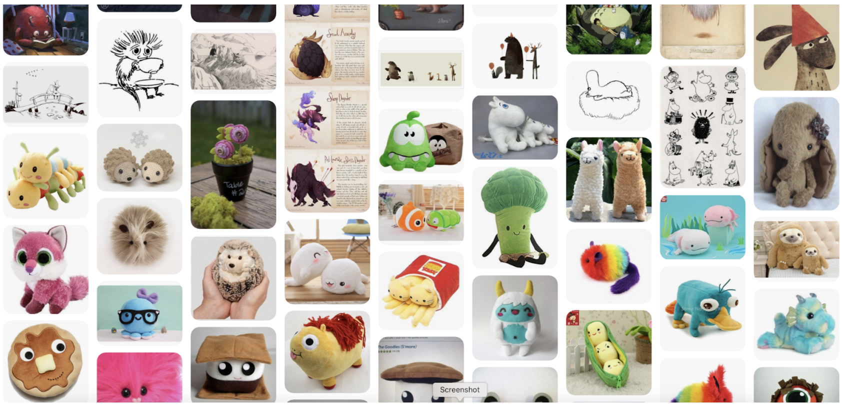
My contribution to this research was primarily the hardware development. The creature body and design were a collaboration between Alessia Cecchet, Ella Dagan and myself, with supervision from Katherine Isbister and Petr Slovak. My contribution to the design was choosing the sensors, processor, and actuators, and integrating the electronics into the device such that we were able to record interaction. I also performed data analysis on the resulting logs to inform refinements of the prototype.

4.3.2 Design Process

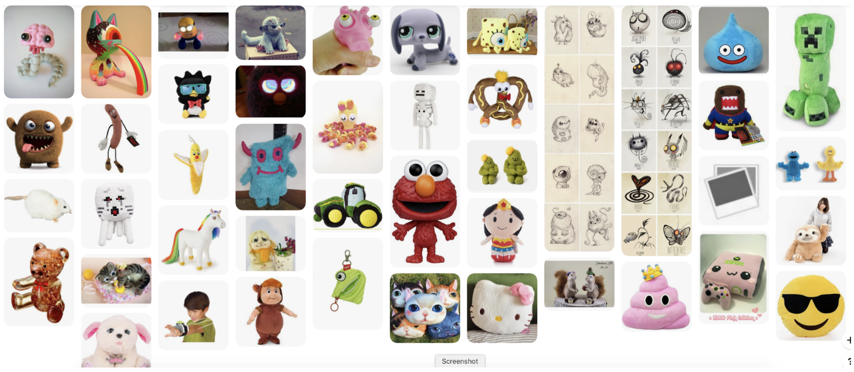
The design process involved interrelated decisions about the exterior and interior of the device that would: 1) enable users to **project** an appropriate persona and invite a particular social relationship, 2) **invite** appropriate self-soothing tactile interactions, and 3) **elicit** (through appropriate feedback) ongoing tactile interactions and social interpretations from the child that scaffolded their emotion regulation. Here we break down iterations of each of these design factors:

4.3.2.1 Projecting a persona/relationship

Early in the design process, we settled on a desired relationship between the child and the creature. The child should feel that they could be a caretaker for the creature, supporting it in calming down. But at the same time, the creature should not seem as helpless as an infant. Instead, the creatures should seem as if it could learn to master its emotions, and become empowered. So the creature should seem vulnerable, but also capable [45]. In terms of what sort of creature it would be, there was interest in providing soft, fuzzy fidgetable surfaces–so we never envisioned the creature as humanoid. There was concern about making the creature any particular sort of animal, because there could be strong associations with real creatures that children might map onto the device (including particular learned likes and dislikes and expectations of complex behaviors). We aimed for an ambiguous creature that had familiar affordances (face, ears, limbs, maybe a tail) without evoking a particular species. We knew from the beginning that we did not want to give the creature a mouth, as we did not intend to engage the child in conversation, and we did not want to settle a clear expression on the creature's face. Rather we wanted its emotional state to be read from its haptic feedback alone.



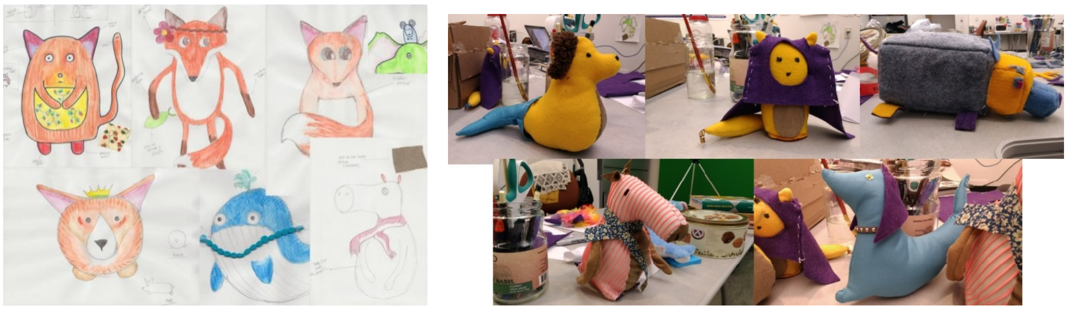
(A)



(B)

FIGURE 4.12: Mood board images used in design process for desired (4.12a) and undesired (4.12b) qualities.

To help the team ideate the creature's appearance, we created positive and negative mood boards (figure 4.12) of existing creature images and toys that had features like those we intended to create. The positive mood board showed cute, but also not too baby-ish creatures, with an element of wildness. The negative mood board included overly baby-ish or emoji-style characters. We



(A) Sketches of creature ideas (B) 3d mockups of creature ideas

FIGURE 4.13: Early designs developed from the mood boarding workshop

moved from these to sketches of various creature ideas (figure 4.13a). Some of these were hybrids of familiar creatures which we did mock up (figure 4.13b), but we abandoned this approach in favor of more completely ambiguous creatures. The final prototypes of the anxious creature from this first phase (figure 4.14) were used in the focus groups presented below. The mottled fur suggests that the creatures have been living on their own for a while, and have some kind of independent existence. We settled on a very simple face without clear expression, and we included ears, feet, and a tail to provide a range of fidgeting surfaces with different affordances. The creature posture was a neutral one, onto which a child could project a variety of emotional states (e.g. not fully relaxed or prone, not standing upright, leaning neither forward nor backward in approach or avoidance). In these initial prototypes, we experimented with providing the creature with a bit of clothing (left, a traveling cloak) to underscore its autonomy and independent life and adventures, and even with a smaller companion (right, riding atop the head) to mirror the relationship between the child and the creature.

FIGURE 4.14: First complete prototypes of anxious creature concepts.

4.3.2.2 Inviting tactile affordances

Here we drew upon prior research examining a variety of soft-bodied fidget affordances [3], as well as work that collected self-reported fidget behaviors from children and their caregivers, exploring links to emotional and cognitive regulation [8]. The latter work emphasized the importance of providing squeezable surfaces, as this was a frequent fidget behavior for children in times of stress. So, the body of both prototypes included an internal pressure ball sensor, embedded in a soft batting that invited gentle squeezes/hugs. We constructed the creature ears from a copper mesh that could be manipulated and slightly reformed, that also had pressure sensors. We imagined that children might manipulate the ears into shapes that they thought mirrored the creature's emotional state as part of their play. Because children also really enjoyed clickable fidget surfaces in the prior research [8], we put clickable buttons into the creature feet. We also gave the creatures a flexible tail which could be squeezed and gently manipulated, that had some stiffness so as to aid in the creature's balance. As with the ears, we thought children might reposition the creature's tail to help indicate how it was feeling. Each of these affordances provided sensor data to a central processor. To keep the creature small enough for a child to hold it, and light enough for them to easily manipulate it, we chose to use Adafruit Feather development boards. We selected the FeatherM0 for the microcontroller board, and added FeatherWing attachment boards with a real-time clock and micro-SD card so that we could log time stamped data in the event of multi-day, in-home trials.

4.3.2.3 Eliciting ongoing interactions

The key to scaffolding children's emotional regulation, we postulated, would be providing an ongoing interaction between the child and the creature that evoked self-soothing fidget patterns from the child as a way to engage the creature. We crafted a backstory in which the creature arrived one day on the child's doorstep, and was easily scared and nervous from its (unknown and mysterious) past experiences. The creature would 'wake up' anxious, and would need to be soothed by the child using tactile interactions which also happened to be soothing for the child as well. These gentle tactile actions would eventually put the creature into a happy, relaxed state.

In developing the interactivity, it was helpful to make use of the MDA (mechanics, dynamics, aesthetics) framework from game design [46], conceiving of the interaction between the child and the creature as a kind of game loop. The child is motivated to calm the creature, and takes actions to soothe it. The creature's feedback helps to guide the child's actions toward self-soothing behaviors. So, the aesthetic in this case is a mutually soothing interaction that builds a sense of competency in the child in their caregiving of the creature, which also leads the child to feel calmer. The mechanics of the interaction are purely touch-based (activating various sensors through manipulation of the creature). The resulting dynamics that we crafted were haptic-motor-based state changes–the creature 'woke up' with a rapid 'heart beat'. Soothing touches would gradually slow the heart beat, which would eventually change to a gentle 'purr'. In this early prototype, it was necessary to press one of the foot buttons to 'wake' the creature and begin the interaction (so as to avoid draining the battery with extended 'listening' for touches when the device was not being used). If the creature was only 'woken up' without further interaction it was on a timer that stepped the heart beat down until the motor was off or 'asleep'. This cycle would happen sooner if the creature was interacted with in a soothing manner.

The final creature design as a result of this first stage, which we used in initial focus groups with children, is shown in figure 4.15.

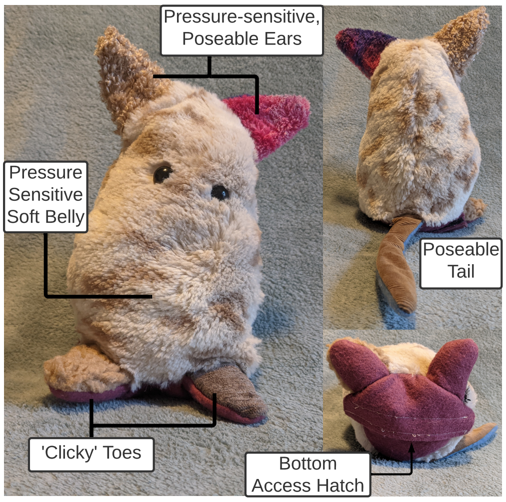


FIGURE 4.15: Anxious creature research prototype used in workshops with children.

4.3.3 Beginning to Articulate a Design Space

In constructing our first full prototype, we found that we were evolving a notion of an 'intimate space' set of interactions, in the sense of Edward Hall's study of proxemics [1]. Hall observed that interpersonal interactions took place at varied distances, and he characterized these as public, social, personal, and intimate space (see figure 4.16). We decided all interaction with the anxious creature should be focused on the intimate space–bringing the creature very close, handling it, even hugging it. Developing this notion helped us to get clear on what the creature would not do–it would not engage the child in conversation, for example, which takes place in the personal and social space zones. This meant we did not need to focus on developing facial expressions or gestures for the creature. Rather we could focus on what could be best sensed in the intimate zone–touch and vibration. There is precedence for using proxemics as a framework in both play design [47] and in evaluating human robot interaction [48, 49]. While game designers have at times focused on intimate-space interaction [47], we did not find human robot interaction characterized in this way in any prior work. Instead, proxemics focused work concerning robots has so far looked more at human behavior at the public, social, and personal space distances (e.g. [48, 50]).

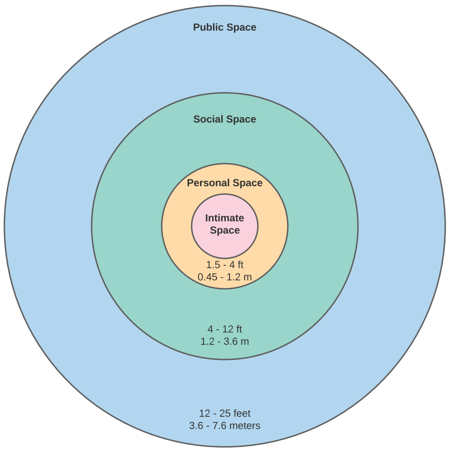


FIGURE 4.16: Hall's taxonomy of social use of space, known as proxemics [1]

4.3.4 Workshops and Focus Groups with Children

Here we report two touch points with the target age group, that helped us to refine the design before our field validation.

First, before we had design mockups and in parallel to the design process, we used plushies chosen from among our positive mood board candidate images to engage children in informal interviews that explored the general design concept. We hosted two workshops with 6 children ages 7-11, that had five activities: 1) Children were asked what the creature should look like and not look like (using samples from our mood boards printed on cards); 2) Children were invited to elaborate on the idea that the creature appeared on their doorstep one dark and stormy night, using a storyboard format; 3) children chose one of the plush toys to enact how they might interact with the creature to calm and reassure it, and were asked to explain why they preferred that particular toy above the others; 4) children were asked to draw and explain where the creature might live in their home, and 5) children were asked how the story might end– would someone come to bring the creature home? Would it live with them forever? In terms of appearance, children were positive about the candidate mood board images and the range of sample plushies that we provided. They were intrigued by the story and glad to demonstrate how they might engage the creature once it arrived. Their playacting included a wide range of activities which blended elements of the creature signalling how it felt, and their own actions to calm it. In terms of the latter, hugging was popular, and some tickled the plushies as well. In terms of the former, children bounced the creature to indicate excitement, and talked about how it might signal its feelings with its face (including its ears). The children assigned the creature very different feelings and reactions in their playacting, which underscored the importance of leaving room for interpretation and free play in the engagement. This range of interpretation also helped clarify for us the importance of a very clear feedback loop to the child about how the creature was feeling in any given moment.

Next, after settling upon an initial design and creating the first functional prototype (figure 4.15), we sought children's initial responses to what we had created. Would they 'read' the creature's appearance as we expected? Would they respond to the touch affordances in the ways we imagined? Would the interaction 'game loop' be legible, motivating, and enjoyable for them? We conducted 3 focus groups with children ranging ages 4-12 (6-10 was the main age range, the extremes (4 or 12) were siblings) to address these questions. All were recruited from an area that was within the lowest 5 percent nationwide on the index of deprivation in the UK. Participants were a combination of White-British and BAME-British background (BAME stands for Black, Asian, and minority ethnic, a UK demographic). In each session, there was one sample creature passed from child to child (2 groups had 4 children, the other had 5. There were a total of 6 female and 7 male children among the groups). At first, children were allowed to explore the creature at their leisure, then parents or the experimenter would prompt them to try to "calm the creature". Initial exploration with the creature was fairly free-form, with only occasional prompting from adults, and guided hand-offs between children after 5 minutes of interaction. At the end of the session the experimenter led a 15-minute question and answer section with the group of children.

To explore the legibility of the creature's appearance, we looked at impromptu comments children made while engaging with the prototype, as well as comments during the interview portion of the sessions. Comments from children related to the creature's appearance included: 'He looks quite cute' and 'It looks like a kitten or something.' In terms of inviting tactile affordances, we looked at children's comments, as well as video coding their interactions with the prototype. Comments included 'It feels good' and 'It looks comfortable.'

We coded video of the sessions, tallying each interaction that happened within a 5-second period (we did not yet have the sensor data log function complete at this stage). If the same action lasted longer than 5 seconds, it would be counted as an additional instance of that action. The coding scheme was built from the bottom-up by examining the videos for common patterns [51]. The creature was considered to be cuddled if the child rested it against their chest, or cradled it in their arms. The creature was 'stroked' if scratched, petted, or rubbed actively in an area, rather than just held. This means that a creature could be held to the chest and scratched on the back at the same time, and both would be counted. The creature was considered to be shaken or thrown when rocked violently or thrown into the air. We originally also coded the number of interactions with the feet, but this action was conflated with 'waking' the creature up and couldn't be effectively separated from genuinely fidgeting with the feet.

Child: Gender:	**1A** M	**1B** M	**1C** M	**1D** M	**2A** F	**2B** M	**2C** F	**2D** M
Cuddles creature	2	5	24	6	14	4	35	1
Strokes creature:								
-On head,back,sides	3	3	9	12	20	5	49	11
-On belly,face	3	1	4	2	3	-	11	1
Throws/shakes	14	2	20	-	31	2	8	1
Plays with:								
-tail	1	-	4	-	2	-	4	-
-ears	2	1	4	-	1	-	2	1

Table 4.1: Tally of natural interactions with early prototype during workshops. 4 children in sessions 1 and 2.

Child: Gender:	**3A** F	**3B** F	**3C** M	**3D** F	**3E** F
Cuddles creature	8	3	8	4	6
Strokes creature:					
-On head,back,sides	-	8	6	1	3
-On belly,face	2	3	-	-	1
Throws/shakes	1	8	1	2	6
Plays with:					
-tail	-	1	-	-	-
-ears	1	-	-	-	-

Table 4.2: 5 children in workshop 3.

The most common touch behavior by far was cuddling (110) and stroking (164). The children did manipulate the ears and tail, but far less than other touches, and not in a manner that suggested they were play-acting the creature's feelings. Another fairly frequent behavior was throwing or shaking the creature to 'wake it up'. This led us to realize that we needed to include some kind of motion sensor in the creature, that we could use to build in a negative haptic response to rough handling in the game loop, in future.

To explore whether the game loop was legible, motivating, and enjoyable–successful at eliciting ongoing interactions–we looked at spontaneous comments during play as well as the end-of-session interviews. In general, children were able to sense and respond to changes in the haptic feedback from the creature, and mapped these responses to the notion of the creature 'calming down' and 'going to sleep'. Their comments indicated understanding of the creature's states, for example: 'You're going to make him stressed... He don't like being stressed, he likes being happy' and 'He's stressed, he needs a nap.'

4.3.5 From Exploration to Duplication

At this point, we planned to move to field study of the creature as a possible intervention. To get ready for this, we made an iteration of the creature that would: 1) tune its external design, touch affordances, and interaction mechanics and dynamics, based on what we observed in the focus groups, to maximize its effectiveness as an intervention to scaffold emotion regulation and 2) make it more robust for a planned in-home deployment–to move from a prototype to what Odom et al. characterize as a 'research product' [52].

The creature's appearance and role was quite legible to the children, so we did not make major changes as a result of their response to these aspects of the design. However, we did make some changes to the exterior design to address issues of durability for unsupervised, multi-day in-home use. Initially, the creature had a Velcro-closed bottom that could be opened to pull out and replace the battery (figure 4.15), but the placement of the access hatch still made it difficult to access the interior electronics for long-term care, while doing little to disguise the hatch from the children. So instead, we created an opening at the side of the creature that allowed for easier access to the core of the plush (figure 4.17). We sealed it with an invisible zipper that matched the creature's fur color to mask the location from immediate inspection.

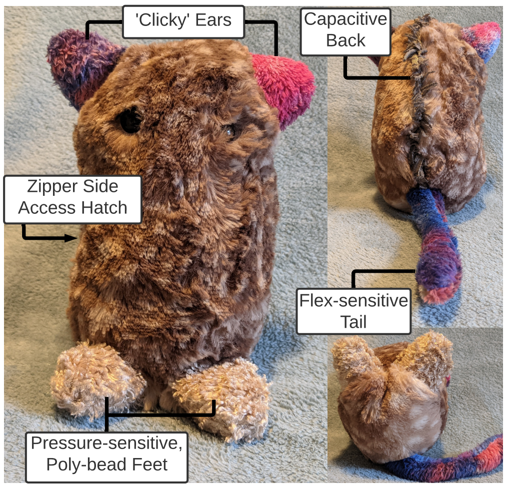


FIGURE 4.17: Key features of the second iteration of Anxious Creature.

Additionally the initial design of the creature had very little protection for the primary microcontroller stack, so a box was inserted around the core which provided some protection from both the poly-fill stuffing and diverted some of the impact force that accompanies squeezing (similar to how a cell phone case diverts impact pressure from your phone). The researcher could use this same opening to connect a USB cable to the microcontroller for easier battery charging and retrieving in-situ captured time-stamped data logs of interaction for post-deployment analysis.

We didn't have enough of the previous faux fur to make the 10 multiples needed, so we sourced a similar fur to make the multiples of the creature needed for an in-home deployment. Otherwise, body shape and other features remained essentially the same.

In terms of touch affordances, we made a number of changes. As we mentioned in section 4.3.4, children in the focus groups were not repositioning the tail and ears as we had imagined they might, and did not touch these areas of the creature much. We decided to try out an alternate design strategy for these extremities. We moved the circular Force Sensing Resistor (FSR) sensors that were initially in the creature's ears into its feet, positioning them between poly-bead fill to create a smooth rolling texture. The idea here was to offer this as a positive 'foot massage' style engagement with the creature. We moved the mechanical click buttons from the feet to the creature's ears, and removed the copper mesh in the ears and replaced this with soft sheet foam. The idea was that this interaction would feel more natural–the clicking embedded in the foam might feel more like manipulating an animal's cartilaginous ears. In the game loop, we recharacterized this as a negative behavior that agitated the creature. In the tail, we substituted the stiff wire placed originally to balance the creature for firm stuffing and a flex sensor that would enable us to sense when the tail was twisted or folded, which we also categorized as a negative behavior that the creature did not like, in the revised game loop.

We found that children would hold the creature to their chest but were not often hugging the creature strongly enough for the pressure ball in the interior to detect anything, so we removed the pressure ball sensor in favor of additional stuffing. We noticed that the hugging was typically accompanied by stroking the creature's back, so we added a capacitive touch peripheral board to our controller stack. To integrate it well with the creature's short fur, we fringed the outward facing edges of a solid strip of the conductive fabric and inserted it into the center back seam, with a solid bare wire sandwiched along the backbone of the creature, stitched in on either side by the rest of the body fabric. The solid wire was then connected to the capacitive board. The visibility of the conductive fabric served also as another stimulus for the child to engage with. This made the material look and feel naturally part of the creature, keeping its exterior feeling soft and plush. It made detecting any petting/stroking motion on its back possible.

Finally, because we noticed children sometimes engaged in some aggressive shaking/tossing of the creature when waking it up, we added a gyroscope and used a moving average filter so that we could address these kinds of touches in the core game loop–abrupt motion would be perceived as negative by the creature.

In terms of the core game loop and interaction with the creature, our motor was originally controlled directly from microcontroller. For the research product version, we added a haptic controller (TI DRV2605) to make vibration pattern and timing easier to control and manipulate. Then, we recreated the basic heartbeat-to-purr haptic game loop for the in-home study, but with a few changes. First, we introduced the notion of negative touches–a rough shake, or playing with the ears or tail, could lead the creature to become more anxious. Whereas stroking, hugging, and foot massages calmed the creature down. Instead of a foot press to initiate the interaction, we embedded an on-off switch inside the creature's body, and put in a battery with much longer life, so that the creature could be sent home and remain on, only periodically needing to be recharged. This meant that we could use motion detection from the gyroscope to initiate interaction with the child. If the child woke the creature gently, it might begin in the purring mode, but if it was shaken, it would wake up anxious. This alteration meant that a child could nurture the creature and enjoy its company without it beginning in anxious mode every time. We made a number of small iterations to this revised game loop through internal testing before the in-home deployment, until the interaction seemed legible to our design team.

To summarize, the role and appearance were already legible to the children and so not changed much, but touch affordances and also the core game loop were amended based on the focus group results. We switched from a free play/play acting notion of how the ears and tail might be used, to a model of giving the creature some touch areas that led to negative responses, helping to shape the children's fidget patterns. And, we tuned the game loop accordingly.

After all of the changes were settled upon, we expanded production to 10 creatures, 8 of which were used for user testing, with 2 for in-house demonstration and maintenance rotation. Figure 4.18 shows multiples of the creature–note that the individual creatures had varying ear coloring, to help encourage children to see them as unique individuals, if they were exposed to more than one of the creatures initially.

FIGURE 4.18: Multiples of research product.

With this revised creature, we then conducted a smaller focus group-style interaction with two pairs of children, to ensure that the new details were legible and producing the responses that we intended. These sessions took about 20 minutes and happened in a quiet room without parents present. All children were approximately 8-10 years old.

In these sessions, the children were observed to immediately attempt soothing behaviors on the creature. One child held the creature to their shoulder for the majority of the session without prompting, while another attempted to gently scratch the front and back of the creature for the majority of the session. Most children seemed to be hesitant to agitate the creature, avoiding contact with the ears and not shaking the creature. As with the first set of focus groups, all of these actions suggest that the design was working as desired–eliciting and rewarding caring, soothing behavior. When prompted by the experimenter to explain their understanding of the creature's vibration pattern, children talked about the 'fast heart rate' or 'cat-like purring,' suggesting that our haptic vocabulary was at least partially understood.

4.3.5.1 Evaluation of First Research Product

We then conducted 2 in-home deployment studies (total of 25 families, n=14 and n=11) to test the potential of the intervention with children for scaffolding emotion regulation. The results of these studies have been reported in two papers [4, 39], with particular emphasis on the psychological effects that the devices elicited in children and adults. While this influenced the alterations to the design it was primarily work performed by our exterior collaborator and as a result I'll summarize the findings that impacted the design changes but will not go into great detail. For more information please see the cited work and the ToCHI journal paper that is in review [6].

In essence, children reported forming an emotional connection to the toy, and using it for emotion regulation. Here we briefly return to that data to highlight how the children and parents responded to specific design choices about the device itself, drawing on the same thematic analysis methodologies and process as described in the previous work. Questions we were interested in within this context thus included:

Was the role legible and appealing to the children? Across both deployments, nearly every child (23/25) named their toy and treated it as a living being that needed to be cared for, with feelings and mental states they seemed to take into consideration. The toy was readily adopted as a social partner, with children reporting they played games together, watched movies, engaged in pretend play, or slept in the same bed. In all these instances, the children were framing the experience as that of a partnership: the toy was actively involved in the activity; or transforming the experience by being close. Most of the references to the creatures' 'emotions' have been directly linked to the interactivity (e.g., the 'heartbeat') and the projected impacts of child actions on the creature's emotional state or mood. In doing so, the majority of the children also built nests or other physical objects (e.g, clothes) for their creatures, to 'make sure' the creatures felt 'comfortable' and 'safe' in their new environment.

Did the device evoke appropriate caring touch behaviors? The high level of care and frequent touching behaviour has been a strong common thread across the interviews with children and parents as well as across the two studies. None of the parents or children reported any negative or violent behaviour toward the creatures; in fact, many children have specifically instructed others as to what kind of touch their creature likes, and made sure no one would 'hurt it'. This shows that although the children were oblivious to the placement of the sensors, the selected location and sensitivity enabled a range of touch behaviours that were still legible and evoking meaningful interactivity without turning the interaction into a overly simplistic gameplay (e.g., the creature reacts to stroking of the back, but nothing else).

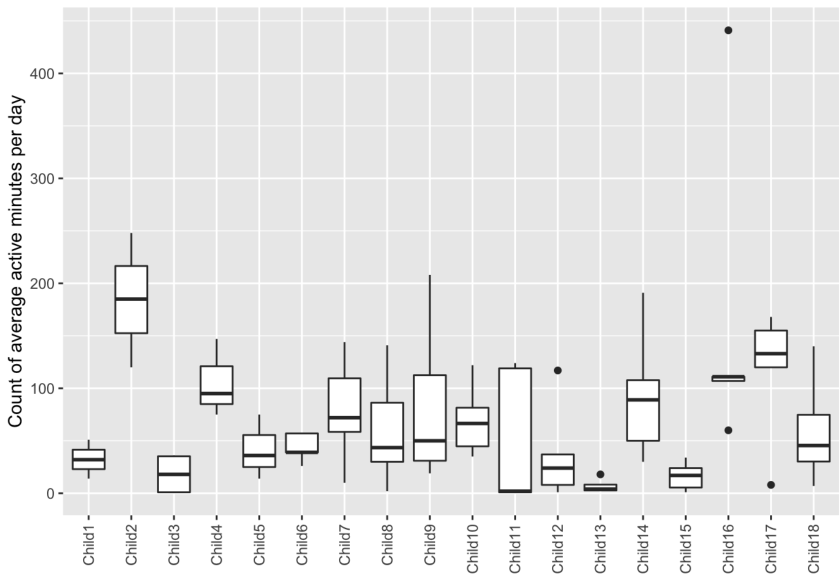
Was it engaged with frequently? As can be seen in figure 4.19 the trace logs from the toys during both deployments show regular interaction with the toy. In particular, children seemed to interact most regularly with the back of the creature, suggesting that hugging or stroking occurred on a regular basis. It was also notable in the data that even during long periods overnight and during periods when no other sensors were active, the tail sensor was often triggered suggesting that the sensor itself was reading false positives. We have removed the tail data from the diagrams shown in figure 4.19 as a result, and the design team noted this for the future revisions as something that needed addressing.

During the field trials children often noted family members playing with the creature, so it's possible that this data reflects multiple people in the household, but even that shows us that the creature is facilitating interaction. For more details about individual children see our analysis papers [4, 39].

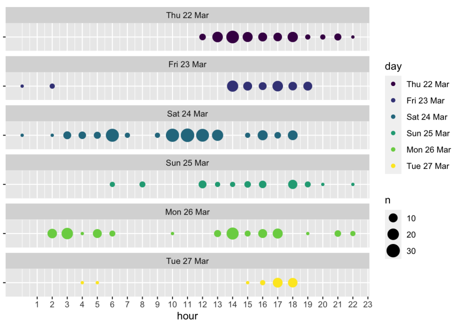
Were the creature's responses in the 'game loop' legible and appealing? As already indicated in the first section of the findings, both children and parents projected emotions onto the devices, saw their interactions with the device as meaningful and impactful (in terms of affecting the state of the device), and did not report any inconsistencies they would notice. We argue that it was likely the ongoing legibility and stability of individual interactions which enabled the development of the broader caring relationship: the game loop was understandable and seen as consistent over time (illustrated by the myriad statements in the format of "my creature likes ¡this¿, but not ¡this¿"); it was not overly simplistic (as illustrated by the intricate stories and emotional projection both children and parents reported above and in prior work [4, 39]), and finally, it was appealing (as illustrated by both the ongoing interaction as well as observations from children and parents describing the feelings of happiness or calm during the interactions with the toy).

4.3.5.2 Limitations

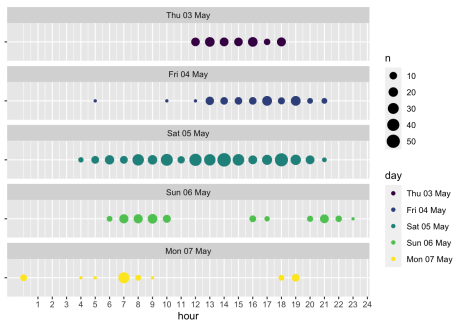
From a design intervention point of view, this first research product was a success–the device affordances were legible and had the effects we intended, and the intervention strategy showed great promise. However, as we mentioned in the introduction, the gold standard for wellbeing interventions in the health field is really controlled trials with a far greater number of participants than we had in this initial home deployment. Yet the team was stretched to achieve this



(A) Daily active minutes per day during the first field deployment.



(B) Child 14 hourly activity count over deployment



(C) Child 16 hourly activity count over deployment

FIGURE 4.19: Touch trace counts per child from the first deployment. With two data breakouts provided for Child 14 (4.19b) and 16 (4.19c).

device deployment to 25 families–we only had produced 8 units that could be used for research, so we had to rotate them among families. To create even that many devices took many hours of researcher time–one of the students felt she'd turned her home into a sweat shop where she was sewing for hours. And, the devices were fragile–the haptic motors started to fail and needed to be replaced. Using larger batteries helped with deployments, but could not last longer than 3-4 days and were cumbersome to replace (something which wasn't realistic to do by parents). As a result accomplishing even week-long deployments required the research assistant to physically travel to participants' homes to replace batteries. Transferring data from the devices was also cumbersome and time consuming.

4.3.6 From Research Product to Commercial Partner

Fortunately in our case, the non-profit that helped to fund the initial device design, development and research, was excited by the potential shown in this initial study, and was very interested in advancing the project forward toward an eventual commercial release. They saw this device as something that could complement their existing emotion regulation curriculum for schools, providing a child-led and situated intervention that could be used by students in the home; thus addressing one of the key issues across SEL programs – transfer of interventions from school to homes. They brought a new partner into the project–a product development company with an extensive background developing health-related socially assistive robots, that was very interested in evidence-based design.

With this new partner, we could work together to produce an even more robust research product that we could use for RCTs and a wide range of research contexts, along the way to the product company developing their eventual commercial product.

In essence, this newly formed larger team had two parallel objectives: 1) creating a robust research product for conducting continued research into the efficacy of the intervention and 2) creating a commercial product prototype that would successfully appeal to markets the company identified. The latter objective introduced what Ko et al. [53] term 'adoption-focused design' into the process. At the foundation of both objectives was the importance of developing a research-validated intervention (valuable to all parties). Beyond this, there were slightly different considerations for each: for the research product, we were primarily interested in introducing robustness for field trials. We also wanted to keep the possibility space open for further development, so we wanted flexibility in the underlying platform. The commercial product focus was on price point and market appeal (as per Ko et al. 2015 [53]).

4.3.6.1 The New, Translated Design

The company spent some months working from the material developed and delivered from the initial findings of the research team to create the product prototype. In figure 4.20, we show the company's product prototype, Purrble.

The company modulated the design to look more like a real-world, albeit ambiguous creature. The fur is a more neutral color. The company's creature looks a bit more childlike, with a rounder belly and wideset eyes. One interesting carryover is that the company worked very hard to keep a wild, individual quality to the creatures, by paying close attention to how they sourced the plush. They chose a plush that had subtle variations in color and pattern, staying away from more uniform and cheaper fabrics based on our advice from the workshop.

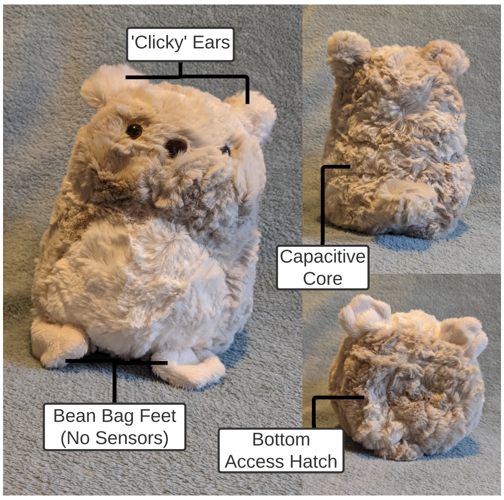


FIGURE 4.20: Diagram showing key features of the final commercial design.

The sensor placements in the creature were similar but not identical–the child could play with the feet and the ears, as well as a small tail. Initially all three had sensors (manipulating clickable buttons in the feet and ears produced positive response in the creature, and pulling the tail negative response), but the final production version removed sensors from the feet and tail, with non-electronic beanbags added to the feet. Children could also hug the creature to influence how it felt. Instead of using conductive fabric on the back, the company used capacitive sensors internal to the device to detect hugs and stroking. As with the research prototype, the company included motion detection so that the creature knew if it was picked up, and handled roughly versus gently.

An important shift that the company made in terms of feedback to the child, was to replace the on-board motor haptics with a sound speaker-based response from the creature. The haptic motors were an ongoing failure point during the research deployment of the prototype creatures–we had to replace many broken ones. They were also relatively expensive. The company knew of sound speakers that created vibration that could mimic a motor's haptic feedback, and these were used instead.

The company also spent a great deal of time elaborating and refining the core gameplay loop for the creature. They kept the fundamental cycle: the creature would become 'anxious' and show this through a rapid heartbeat, and could move into a calm happy state, shown with a purr. However, the company added some more subtleties and modulations. For example, they added gentle sounds made by the creature both initially, and in response to touch, that vary according to the creature's heart beat.

4.3.6.2 Tuning the Interaction

Once the company had built the new product prototype, they distributed initial copies to the research team, and we collectively engaged in a series of iterations based on engaging with these prototypes and with subsequent updates to both hardware and software. Alongside this ongoing dialog, the company was also introducing the device to people in their target markets, collecting their feedback as well, and using it to make adjustments.

One area where adjustments were made was in refining the balance of the sounds and the haptic feedback. The company ended up including a switch that allowed end users to modulate how much vibration was part of the interaction– 'low mode' had less, and 'high mode' had more.

The hardware had to be adjusted as well, because of issues introduced by swapping the conductive fabric that was part of the research prototype (figure 4.17) for capacitive touch sensors. The sensitivity and placement of the first set of capacitive touch sensors led to the device not picking up on the full range of hugs and pats from users, which then caused their mental model of the game loop to fail. Also, some who picked up and held the first prototype didn't like the hard, ungiving sensation of the internal frame. The company made changes to make the device feel softer, and to increase the responsiveness of the sensors to key types of touch from users. Key changes focused on tuning the touch tracking, to create a consistent game loop that accommodates different patterns of petting and holding the creature.

Finally, the company made many small, subtle tweaks to the core game loop that were software based, and thus easier to change. During this stage, the company would frequently circulate new versions of the code base for the researchers to test out. Both teams also had potential end users and their caregivers try out the interactions to check for their legibility, in moving toward the final release version.

4.3.6.3 Validating the Translated Device

The full research/company team did not engage in a formal comparison test of the research prototype versus the product prototype, but we did collect reports and insights across a variety of sources that help verify that the company's product design replicated the core interventional aims of the research prototype.

For a more detailed analysis on the progression between research prototype to final product, I again refer you to the full ToCHI paper [6]. Here is a brief summary of some findings from interviews with a counselor who worked with the team to deploy both device versions with children. The counselor noted that children were 'caring and nurturing' to the new model, and that they 'cradle and sooth' it–both behaviors that we witnessed with the research prototype. The counselor noted that 'it seems to sooth the children and calm them. It looks like it gives them comfort.' When children were upset, the counselor noted that 'there's definitely the sensory, the sort of stroking them, looking down at them, and then they might be too absorbed in their own.. whatever it is that's going on. That they certainly, the touch thing where they're holding it, hugging it, stroking thing, it seems to be the comfort thing.' Also: 'it seems to be very, very soothing, an immediate thing.'

The counselor reported enhanced value from the sounds the new creature made: 'they were charmed that it made noises and was talking to them' and that children are 'definitely talking more with this one.' The counselor noted 'they speak to it and listen for a response' particularly when they were calmer.

Concerning the rounder shape, more baby-like features, and shortened tail of the commercial units, the counselor shared that children were 'much more delicate with these ones. I think partly that's [chuckles] to do with the tail. Because the tail was quite tempting to pick it up and swing it round.' The counselor also noted on first impression that 'this one appeared more fragile.'

Overall, this counselor's impressions suggest that the core design choices and intentions (role clarity, touch affordances, and interaction legibility) carried through in the commercial design, and that the modifications the commercial team made added enhanced value to the experience for children.

4.3.6.4 Reflections on the Translation Process

Overall, the research team was very gratified by how the commercial team adopted and then evolved the design of the creature. Here we provide a few reflections and recommendations for others who might want to work with a commercial team to create a more robust and scaleable version of their work toward creating multiples for larger scale testing.

1) Aligned values. It helped in this collaboration that the company already was very interested in the domain of socially assistive robots, and had prior experience building robots for other health contexts. This meant that they were not trying to turn the prototype into a typical toy, but rather deeply understood the core design ideas. If possible, it is a great idea to find a commercial partner that already has relevant knowledge and experience.

2) Ongoing communication and artifact sharing. It was important to the design translation process that we had ongoing communication, and that we shared artifacts both early in the process, and in the ongoing tuning phase. The in-person kickoff at the company allowed rich dialog about the nuances of the original design, and helped the company to internalize key design values and build upon the original design thoughtfully. The sharing of the physical prototypes, and then the code updates, helped everyone to grasp and give feedback about the design evolution. One really could not understand changes in the core game loop and haptic cues without feeling them for oneself. Overall, the artifacts were very important as communication points (as per Remy et al. 2015 [54] and Concalves et al. 2011 [55], as well as Gaver and Bowers [56–58]).

3) Recognizing and adapting to divergent needs. As we mentioned, the company was working on understanding possible markets and evolving the design to meet those needs, while the research team wanted a device that could support ongoing research. In the process, we realized that certain key features of an ideal long term research product needed to be jettisoned from the commercial prototype, in the interest of cost management and durability. In particular, the ability to collect time-stamped touch trace data needed to be removed, to avoid the necessity of a secondary battery and additional system complexity. Also, specific appearance, affordance, and game loop decisions got made on the commercial path that we might want to vary and experiment with over time in further research studies with different end user populations and contexts.

The research team engaged in extended conversations with the commercial team about how we might create a divergent research toolkit alongside their path to product. This would allow us to continue to conduct research, which would in the long term benefit the non-profit and the company as well, given their evidence-based design focus. The commercial development team agreed to provide instructions and components to the research team, so that we could develop a parallel, 3d-printed, Arduino-driven set of research prototypes to continue to do our work. The research team has used these instructions and components to successfully build devices that we can use as a testbed for further iteration of all of the relevant design variables in the intervention– role and relationship (by changing 'skins' of the device); touch affordances (by adding and changing sensors), and interactions (by modifying the game loop and behaviors freely by recoding the arduino core of the device). This will allow us to engage in a longer term research agenda that takes advantage of the increased durability and scaleability of the commercial design.

4.3.7 Refining the Design Space of Intimate-Space Socially Assistive Robots

The translation process also helped us to more clearly articulate the notion of 'intimate space' socially assistive robots. Based on this translation, we would define such robots in the following way: well designed intimate-space SARs drive interaction in the intimate zone by: 1) evoking for the user a persona/role that is appropriate for evoking intimate-space interaction, 2) providing touch affordances (and an overall form factor) that facilitate intimate-space interaction, 3) providing a feedback system that structures and rewards intimate-space interaction.

To help clarify this design space, we consider exemplars that we found in reviewing the literature around tangibles/ haptics and socially assistive robotics. In the following table, we briefly consider examples of both research and commercial devices we would consider to be in this category to some degree: Paro [19, 29], Haptic Creature [59–61], Huggable [62], Qoobo [32], as well our Anxious Creature (figure 4.17) which became the final Commercial Ready Design (figure 4.20). For each, we briefly characterize the persona/role of the device, touch and other affordances, and the interaction loop.

As outlined in the Design Process, section 4.3.2, our team focused on three key principles during the construction and evaluation cycle, 1) Projecting a persona/relationship, 2) Creating inviting tactile affordances and 3) Eliciting ongoing interactions. Our overall goal was to create a device that would encourage a child to feel comfortable enough to integrate the creature into their intimate interaction circle, toward scaffolding self-soothing.

We settled on some design features that we see in these other robots/SARs, that we believe encourage the end user to welcome the robot into the intimate space of interaction. First of all, the robot is of a small size. All of the robots in the table are easily lifted and carried, and can readily be placed on the lap. At this size, it is convenient, and also nonthreatening, to bring the device very close for petting and hugging. Considering projecting a persona/social role, this size factor works well with the personas/roles that were chosen for each of these robots as well. All of the robots take on the form of an smallish animal that a person would feel comfortable caring for and connecting with. Interestingly, other than Paro, the design choices tend toward abstracted versions of creatures rather than evoking specific creatures.

Let's now consider inviting tactile affordances. All of the examples we include have soft surfaces, encouraging touch. In addition, all have some form of active feedback mechanisms that encourage touch, whether mechatronic movement, haptic vibration, sound, or some combination thereof. Huggable stands out as also providing affordances and feedback mechanisms that are more appropriate to the personal/conversational zone of interaction, with its capacity for conversing in words (vs. animal noises) and its directable gaze. We consider Huggable to be bridging between the intimate and personal space zones of interaction.

In terms of eliciting ongoing interactions, the robots in our table vary in their interaction loops, but a common theme is the use of simplified, stylized versions of responses of domesticated or harmless/baby animals to stimulus and connection. This is true for Paro, Qoobo, and Haptic Creature, as well as for our research prototype and final commercial design.

The interaction loops in all of these robots emphasize eliciting and then responding to touch by the user, forging a positive connection and leading to close attention from the user to the state of the robot. Huggable is in a separate class–it does invite close touch, but also engages the user in a dialog. As a teleoperated robot, it also does not have a clear pre-defined interaction loop. We include it to show that one could incorporate intimate space characteristics in a robot that is also aimed at the personal zone of interaction.

Overall, one can see from this set of examples (tables 4.3,4.4), that there seems to be a class of intimate-space robots that can be fruitfully deployed in socially-assistive situations. In the case of Paro, this is to soothe and engage elders who cannot manage a real pet. Qoobo is a sort of novelty version of this, that makes playful reference to the mercurial moods of cats. In the case of our research prototype and final commercial design, these intimate space design characteristics have been deployed to provide a safe opportunity for self-soothing for children, who can take care of the creature and thus also help themselves. The fact that several research and commercial examples have converged upon these common design characteristics suggests that they have merit when designing for intimate-space SARs. We see this as an emergent useful class of robots worthy of further study and development.

4.4 Further Development and Future Work

Now that our research has been translated into a commercial device, our research partner Petr Slovak has gone on to develop larger studies that can serve as true trials of the efficacy of this type of intervention. One of the major limitations preventing the research team from performing larger studies was that the hand-crafted design, maintained by a single engineer (myself) meant that repairs were difficult to perform. With the mass produced Purrble on the market, available since December on Amazon, Slovak is able to more easily distribute devices for clinical trials.

However, an important limitation of the commercial devices is that they do not store touch trace data–they only use it during interaction. This choice was made to reduce cost and complexity of the devices. Our research team worked with the commercial partners to get a handoff of their designs, so that we can reintroduce touch trace memory in modified research devices. In future, I hope that the research team will carry on the work I helped to start, using these modified devices to ask one of our primary research questions: it is possible to detect a person's emotional state via their interaction with a tangible interface? To do so, one would need to gather a corpus of touch traces to support ML techniques. In the next project, we are on our way to doing so with a different user population and device.

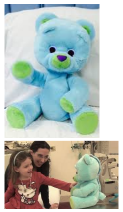
SAR Name	Image	Persona/Role	Touch affordances	Feedback mechanisms	Interaction loop
Paro [19, 29]		Baby seal (emotional support animal)	Soft fur, able to respond to touch on body	Mechatronic movement; cooing sounds	Responds to light, sound and touch; a range of responses meant to imitate engaging a trusting baby animal
Qoobo [32]		Cushion with tail (catlike)	Soft fur, able to respond to touch on body	Mechatronic movement (tail swishes at various speeds inviting stroking)	Attract ’tail swish’, positive and negative tail movement responses (imitating a cat that likes, then gets overloaded with touch)
Huggable [62]		Bear, for sympathetic discussion and touch	Soft fur, able to respond to hug or hand squeeze	Mechatronic movements; screen-based eyes; voice (tele-operated)	Tele-operated combining touch and conversational interaction

Table 4.3: Comparison of intimate-space robots. Part 1

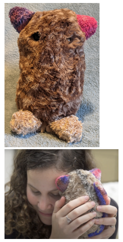
SAR Name	**Image**	**Persona/Role**	**Touch affordances**	**Feedback mechanisms**	**Interaction loop**
Haptic Creature [59–61]		Research platform, resembles a large rodent	Soft fur, able to respond to touch on back	'Breathing' motion, variable ear stiffness, purring	Breathing, ears, purring aimed at communicating preferred touch to user
Anxious Creature		Research platform, emotional support animal	Soft fur, able to respond to touch on back, ears, feet, tail	Haptic feedback (anxious heartbeat, purring)	Haptic feedback meant to invite user to sooth the creature into calm purring
Purrble		Commercial design, emotional support animal	Soft fur, able to respond to touch on body and ears	Haptic feedback (anxious heartbeat, purring) and soft noises	Haptic and auditory feedback meant to invite user to sooth the creature into calm purring

Table 4.4: Comparison of intimate-space robots. Part 2

Chapter 5

Correlating Touch to Action

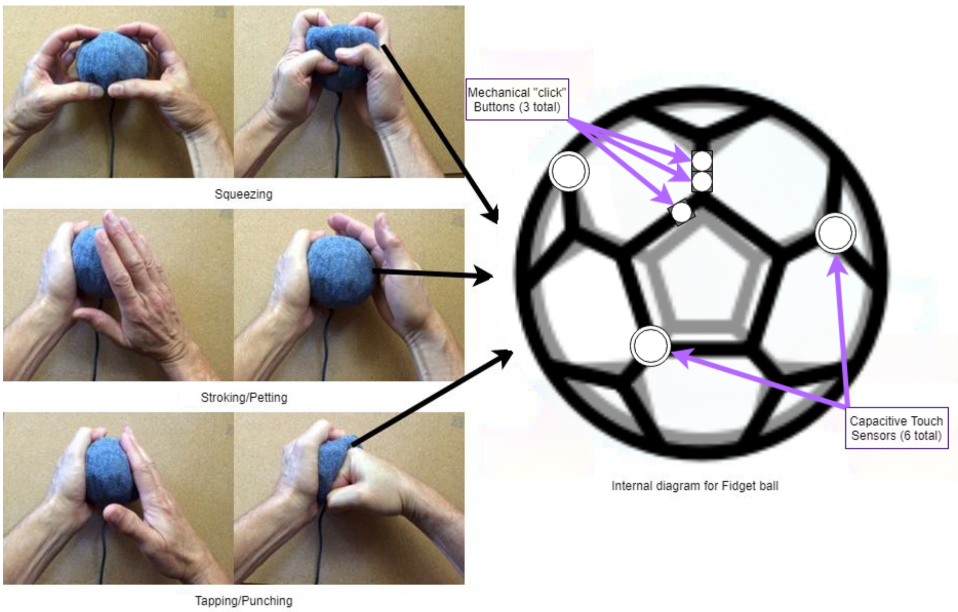


FIGURE 5.1: Sensors embedded in the surface of the Fidget Ball can sense a variety of sensory inputs.

5.1 Purpose

Fidget objects have become massively popular in recent years. In May of 2017, every one of the top 10 selling toys on Amazon was a form of spinner [63], while popular sites recommended stress balls and worry stones to both adults and children as a means of managing stress and improving focus [64]. It seems that manipulating hand-held objects with the right kinesthetic and tactile affordances satisfies an important need in day-to-day life.

We know intuitively that touch carries affect, but we have limited insight into the component problems of extracting affect from tactile data. We cannot enumerate the features of tactile data that carry affect, or directly interpret the affective content in tactile data. However, recent advances in deep learning hold promise for establishing connections between touch traces and affect.

Motivated by this growing appreciation, this section explores the potential of sensor-enabled, computationally enhanced fidget objects for collecting meaningful touch trace data. This work attempts to focus on the intervention and interpretation portion of the core research questions by collecting touch trace data to support ML interpretation and analysis toward better understanding of fidgeting patterns, as well as, in the long run, personalized advice and interventions.

This project was a collaboration with Professor Katherine Isbister and Adjunct Professor Daniel Shapiro. My contribution was the development of the fidget ball (hardware, software, and crafted affordances). I also worked to pilot the user study with 30+ neurotypical users, with findings and user study design transfer to a team run by Julie Schweitzer at UC Davis, who will be running a NIH funded large scale study with participants who have ADHD.

This work was started in the fall of 2017 and has been interspersed with the SEL creature development. Pilot testing was executed in 2019, with a follow up neurotypical study scheduled for 2020. Unfortunately due to the COVID-19 global pandemic, this was curtailed. The UC Davis study was originally slated to begin in Jan 2021, but again due to pandemic related delays as well as the following microchip shortage getting laboratory environments set up delayed the start to commence in summer of 2021. Preliminary internal data from this study is included and I've compared the resulting data streams against results collected previously in my 2018 user study.

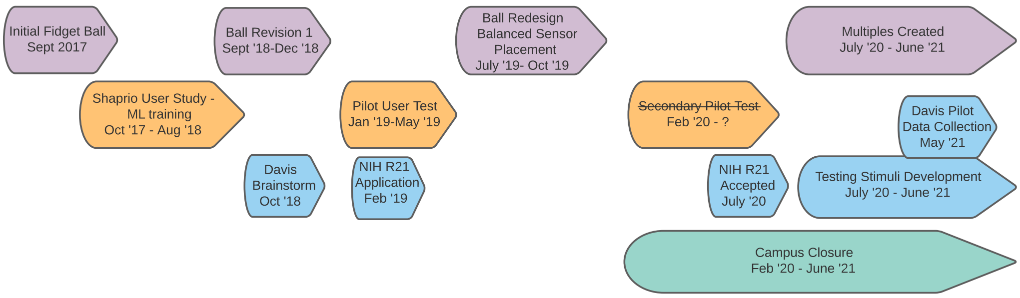


Figure 5.2: Timeline of Fidget Ball between September 2017 to June 2021, Fidget Ball design work related events in purple, UCSC driven user testing in yellow, and collaboration events with UC Davis in blue.

5.2 Design and Development of the Device

The primary aim for our smart fidget device was to construct something that could be used in laboratory and field settings to collect moment-to-moment, fine-grained data about fidgeting behavior. This could then be set alongside simultaneously captured data about focus and task, toward building a richer picture of the impact of fidgeting on attention. Unlike fidget designers looking to attract attention and market share with visual appeal and flair, we wanted to create a device that would provide the right sensory stimulation, but that would not be distracting to others. We aimed for the device to be in a form that would ultimately be acceptable in the workplace, usable by a large population of adults, and could be used either one- or two-handed (to support users in working while fidgeting). In several prior surveys, participants mentioned using stress balls, tennis balls, bouncy balls, racket balls or other spherical objects, so we used this commonly reported form factor. We aimed to provide material properties reported as desirable in fidget objects such as **'pliability, softness, satisfying clicks, squeezes'** [37] by prior work. The final design of the device reflects these design aims.

From an engineering perspective, we needed to construct a device that was rigid enough to protect the internal electronics, while still offering appropriate tactile and kinesthetic qualities. What resulted was the Fidget Ball, Figures 5.1 and 5.3. We drew upon the common 'stress ball' physical format. A soft flexible rubber ball provides the skeletal structure—we used a ball made for dogs to

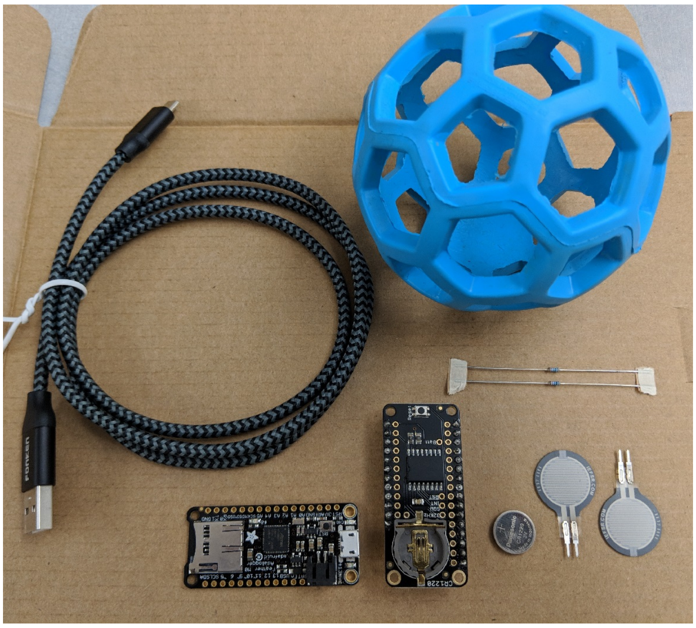


FIGURE 5.3: Core hardware components used in the first iteration of the ball. From left to right: MicroUSB cable, Adafruit Feather M0 microcontroller and RTC add-on w/ battery, JW Hol-ee Roller dog toy, 1K Ohm resistors, and Round Force-Sensitive Resistors. Not pictured, fabric cover and silicon-coated wires.

chew on, that measures approximately 4 inches or 10 cm in diameter. Its pliable nature allows for easy deformation in the first inch of compression by hand, but additional deformation requires significant intentional pressure by hand, and when pressure is released the ball returns to its original form readily. Inside the skeletal structure is a suspended Adafruit Feather M0 microcontroller with a FeatherWing RTC daughter board. Both boards are commercially available and measure 2" x 1" or 51 mm x 23 mm. When stacked together with header pins they measure approximately 7/8" or 2.2 mm. While our team debated about developing a one-handed palm-shaped bean, we could not determine a way to scale down our shape smaller, as it would have been difficult to protect our micro-controller stack without printing custom designed boards, which was out of our means in the prototyping phase. Additionally, the ball lent itself better to being stroked, while allowing squeezing, A bean-like shape would have easily lent itself to compression, but not as well to stroking over the full surface.

As the ball's compression lends itself well up to an inch, but provides significant resistance after that point, the microcontroller's largest dimension of 2" provides a comfortable 1" buffer before pressure on the microcontroller stack might become distracting for the user. The stack is suspended in the middle of the ball via flexible silicon coated wires leading to 6 capacitive flex sensors that are arranged around the outside surface of the ball, organized approximately evenly in analogous positions to the faces of a cube, Figure 5.4. Initially these 6 sensors were the only data that our ball collected. However, we noticed that participants desired more range of fidgeting affordance, so in the final version, we included 3 mechanical buttons positioned near the USB tether, providing pressing and clicking, in addition to the squeezing affordances. Also, during initial testing we observed multiple users attempting to roll or gently toss the ball in the air, so we added an inertial measurement unit (IMU) to extrapolate that information.

To reduce the weight of the ball, and as the ball is intended for use alongside desk work, we avoided using batteries in favor of using a USB cable providing

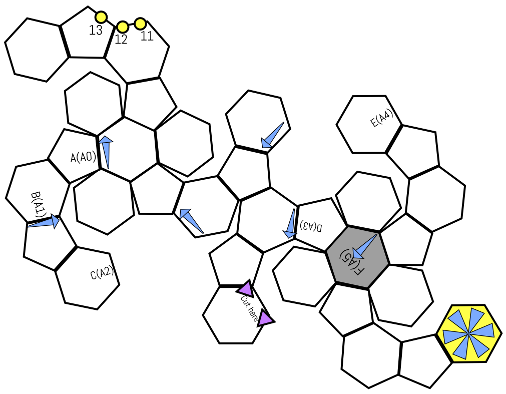


Figure 5.4: Flattened diagram of the final sensor placement around the surface of a mixed hex/pentagram ball. For a full life-sized version see supplemental materials, feel free to print, cut and assemble your own ball!

power and transmitting data directly from the micro-controller to the computer. We reasoned that the tether would not hinder usage by the user and could serve to orient the ball when verifying locations of the sensors.

As part of our original list of affordances derived from our literature review, we desired the ball to be "soft" to the touch. The rubber ball's texture is "tacky" or "non-slip," meaning that we needed a way to soften the texture for our users. We used a fabric cover to both mask the surface texture and disguise the locations of the sensors from users. We chose a fabric that was neutral in color to minimize distraction and avoid biasing use based on strong color preferences or expectations arising from color stereotypes. In future iterations, this could of course be customized and adapted for different user populations and use cases, for example a child might prefer a more playful or colorful design.

5.3 Machine Learning Data Sourcing

The initial device we used to collect data only had the 6 capacitive sensors around the periphery of the ball to collect and correlate user's touch data focusing on the user's emotional expression through touch. This data was used to train a ML algorithm to reinterpret touch into meaningful messages. In this way a user could unknowingly fidget in a sorrowful, happy or distracted manner and be alerted to their underlying emotion by a tweet, song or notification and self-examine their emotional needs.

This study seeks to gather an amalgamation of affective touch for ML training and was designed by Dan Shapiro and Katherine Isbister, modified by myself. Tests were run by myself and Professor Shapiro. This study primarily addresses research question 2: It is possible to detect a person's attentional or emotional state via their interaction with a tangible interface? The reported outcome of the ML training is in the TEI 2019 proceedings paper "Transforming Affective Touch into Text" [5].

While I did not contribute to the development of the ML model, I was responsible for creating annotations for the data samples, developing the data stream, and coding observed behavior from video recordings. It is my hope that data collected from 'smart' fidget devices like this one can be used for real-time detection and intervention to support better attention and emotion regulation, informed by ML models like the one we worked on in this project.

5.3.1 Initial Laboratory Set-up

For the UCSC based user test we sat the participant facing the experimenter at a 5 foot by 2.5 foot table. The participant had in front of them the fidget ball, a directional table microphone, and a computer monitor to their left with on-screen instructions. The experimenter sits to the participant's front right.

In front of the experimenter sat a mac laptop that was connected to the afore mentioned fidget ball and a microphone and was used to collect data throughout the experiment. The experimenter controls the screen to participant's left via a mouse and a mirrored slideshow, the presentation notes of the slideshow on the left side of the laptop. The two monitors are connected to a desktop tower whose sole purpose is to run the slideshow.

The table is situated at an angle in relation to the door such that the experimenter is facing the door and the participant has minimal external distractions with two blank walls behind the experimenter.

5.3.2 Procedure

The study was broken into three sections: Demonstration, Communication, and Interpretation. In all three sections, the users were instructed to interact with the fidget ball in some manner and voice their thoughts which were captured in a speech-to-text program.

FIGURE 5.5: A montage of input gestures from left to right: squeezing, stroking, patting vs punching.

This study had 16 participants ages ranging between 18 and 50, with 31% of participants female. All participants in this section were assumed to be neuro-typical, although participants were not specifically screened.

In the first section of the study, participants were asked to mimic the behavior shown to them by the experimenter, small sampling shown in Figure 5.5. This section was meant to get the user comfortable with a range of actions and focus their attention on the feeling of the actions.

In the second section of the user testing, participants were asked to communicate with the ball through touch and vocalize interactions as if talking with an animal. The user was provided on screen prompting of a variety of scenarios with vague actions to complete. Ex: 'Your pet is sick. Comfort it.' This section was meant to allow a user to naturally connect the actions provided in Demonstration section to actions.

In the third section, participants were provided with segments of lyrics from published songs and asked to translate their interpretation of the song to touch, much in the same way that sign-language interpreters have to translate not just the words but the feelings behind those words toward hard-of-hearing people. This section broke the touch task and the audio task into two, which participants said helped them focus their thoughts on the action, and made expressing their words easier. This interpretation task was meant to assign categorized emotional word sequences to actions, with confirmation of meaning by user's vocal translation.

5.3.3 Successfully Translating Touch into Affect

In Shapiro et al. [5], there is description of the construction of a deep learning system built using this data corpus. The system attempts to translates tactile touch data from the user into textual feedback that reflects the source touch's affective content. This system inputs 10 seconds of touch from the fidget ball, and outputs a song lyric with matching affective characteristics. For example, holding and violently shaking the fidget produced "Control through fear/A reign of terror is here", while slow stroking produced "Baby, if you want to, be my lover/You better take me home". The underlying learning system input the body of touch data with associated textual descriptions obtained during the study, processed the text into an affect vector (for anger, anxiety, sadness, certainty, tentativeness, and positive emotion) via sentiment analysis tools, and acquired a mapping from touch to affect via deep learning.

This translation from touch to affect was made possible by the large rich data stream provided by the attenuated sensor sensitivity and fast response time. We benefited from being able to detect both light and heavy touches at high speed as we were able to detect quick changes such as finger drumming through the device, and the slight bleed-through effect that resulted from the fast read time was a boon to ML analysis.

The fidget ball was sufficiently sensitive to expose conflating effects in the data, as judged by the degradation of affect recognition accuracy when we included task-prompts in the data. For example, "your pet is trying to run into traffic, restrain it". This prompt elicited thorough petting, as well as firm squeezing and holding, which confused an analysis intended to recognize motions with certain/definite character. We've shown how the fine detailed corpus of data obtained through the fidget ball has successfully supported the first nuanced machine learning analysis of affective touch [5].

The symmetric placement of the 6 pressure detectors was agnostic to user grasps, with no noticeable difference between gender or grasp style, this symmetry supports and simplifies the ML solution, and future experimental designs aim to compare more possible factors that affect grasp (i.e. dominant hand preference, interaction based on neurotypical compared to neurodivergent conditions). More broadly, we plan to develop deep learning techniques to examine the structure of touch data and correlate it with a range of fidgeting behaviors, both to classify the character and gestures of touch, and to predict effectiveness of touch strategies on measures related to concentration. To do so we needed to expand our corpus with a range of tagged touch based in both affect and cognition.

We did notice that placement of the sensors within the ball had to remain consistent between ball iterations for the machine learning to be consistent with its output. As such the current deep learning system would need retraining if other form factors were to be considered. Ideally with more data we could expand our system to output more than just lyrics from a particular fidget ball and could expand to reporting tagged emotions that could be translated into multiple varieties of feedback, ie light, sound, or a behavioral log. At this point the corpus is not large enough for work with the machine learning to be called complete, however given that this tool lends itself to further fidgeting research, we could incorporate data collected by external collaborators with their corresponding activities into the corpus as the program progresses. What is clear is that the fidget ball as it is constructed provides a rich stream of data that can be used to create promising ML models of the connection between touch traces and emotion.

While we were successful in developing a model for ML interupretation we also had an ongoing issue in data collection. The localized speech-to-text engine was hard pressed to accurately capture participant's words. Frequently the buffer would be unable to keep up with the user's speech, and those that had accented English were an additional strain on the system. As a result, only a small percentage of participants' speech samples were accurate. In future, capturing raw audio and performing post-transcription would provide better data.

5.4 Cognitive Performance Pilot Testing

In October 2018 we began our collaboration with UC Davis. This research takes advantage of fidget ball's touch trace capture to examine fidget patterns, and is also collecting data to inform machine learning models toward future tailored support of people seeking to adjust their cognitive performance. We were interested in whether we could observe links between fidgeting and improvement in cognitive performance in people with ADHD as compared with a neurotypical baseline population.

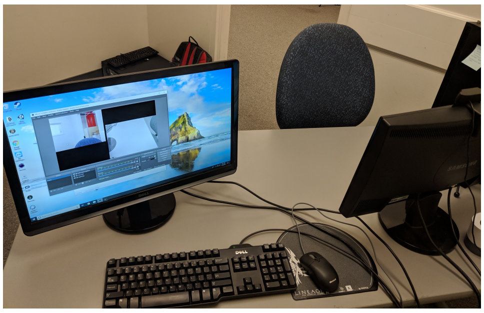
It was my task to collect the baseline data from a neurotypical population. I took the lead on modifying our original protocol and with the help of my undergraduate research assistant, Vicky Feng, we developed materials, reconfigured the fidget ball, ran the protocol and performed statistical analysis on the results.

After consulting with Julie's team, we determined which cognitive tests we should use in conjunction with our fidget ball to quantify users' performance. We developed a protocol that had two tasks that were specific to **concentration**. We also included a task in the study that was aimed at eliciting fidgeting related to particular **emotions**, toward exploring the link between fidgeting and emotion regulation. Between these two we could balance furthering the affective ML data collection alongside starting to collect data as a base line for the work with Schweitzer's team.

I made modifications to the fidget ball for this study, adjusting the design by embedding 3 mechanical 'clicky' buttons alongside the 6 capacitive sensors, while keeping the surface the same soft felt fabric for consistent user experience. This was because prior research suggested that people sometimes preferred a clicking mechanic when trying to focus [8] in addition to the affordances that the ball already provided.

We also slightly modified our laboratory set-up, Figure 5.6. This time around we had participants sat in a chair facing a monitor attached to a desktop computer. The researcher had control of the mouse and keyboard, and led the progression of the session. One camera captured participant facial expressions, the other captured participant fidget behavior with the object. A microphone captured participant responses. All recordings were captured using Open Broadcast Software (OBS). The fidget ball was connected to the computer by its USB cable, and was presented to participants during the corresponding tasks. The researcher sat facing the participant at an angle, with a secondary monitor that reflected the participant's screen. A tablet with a survey pre-loaded was presented to the participants for debriefing. The study was conducted in a well-lit room with a suitable amount of space for the participant to freely move their arms.

(A) The view of the participant, boxes indicate data collection devices.



(B) The experimenter's view of the 2 web camera feeds streamed into OBS.

FIGURE 5.6: Lab setup for user testing.

5.4.1 Demographics

While we initially aimed to produce results from 40 neurotypical participants as a base line against Julie's larger ADHD participants, it quickly became clear that our device was not robust enough to facilitate quality data collection, with an intention to refine the user study and device before resuming data collection in February of 2019. In total we gathered data from 23 participants. 21 right-handed and 2 left-handed, from ages 18-35 years old participated. 13 of the participants self-identified as male, 9 self-identified as female, and 1 self-identified as non-binary.

5.4.2 Procedure

Over the course of an hour we led participants through four tasks, the Paced Serial Addition Test (PASAT) [65], a reading comprehension task, and a series of pre-categorized emotional elicitation videos, followed by a repetition of the PASAT task. Participants were assigned 1 of 4 protocols which dictated task conditions. Participants used the fidget during one of the PASAT tasks, order was randomized across participants. This allowed us to perform a within-subject analysis and account for any learning effect that might result from performing the task twice. The second PASAT task was performed approximately 45 minutes after the first. In half the cases, participants were given the ball during the reading comprehension task, and results were analyzed between subjects. All participants were provided the fidget device during the emotional elicitation video task, toward building a corpus of emotion-related fidgeting behaviors. To get a sense of how tasks were affecting participants, after each separate task, they filled out a 4-question survey on a 9-point scale:

1. How positive do you feel currently?
2. How negative do you feel currently?
3. How positive did you feel during the task?
4. How negative did you feel during the task?

5.4.3 Detailed Description of Tasks

The PASAT, **a concentration intensive task,** was presented as a powerpoint of 60 slides. Each slide contained a single digit between 0-9 and was displayed for 2.4 seconds (Inter-stimulus-interval) before automatically progressing to the subsequent number. Participants were instructed to retain the number on the previous slide and add it to the number on the following slide and verbally announce their sum. Participants were led through 5 examples of this addition by the experimenter, and participants were allowed to confirm proper procedure before the test began. This test aimed to measure fidgeting behavior during cognitively taxing sessions.

In Task 2, the participant had 3 minutes to complete the Woodcock Johnson III Achievement Test (a reading comprehension and **concentration** task) [66]. At their own pace, the participants read a series of short statements and stated whether each was true or false. They were told to complete as many as they could within the 3 minutes. The participant would answer the questions using a computer mouse in their dominant hand and were asked to hold the fidget ball in their non-dominant hand. This task aimed to capture fidgeting behaviors during sustained cognitive loads.

After the Reading comprehension test debrief, participants were offered a 5-minute break.

In task 3, participants were shown a series of 8 videos selected from a Gross & Levenson [67] study of **emotional elicitation** through film.

We targeted emotions that would be most analogous to categories from the Linguistic Inquiry and Word Count (LIWC) [68], a sentiment analysis tool used in coding textual data into information that can be used by machine learning systems. While LIWC provides a wide variety of categories, the overlap with prelabelled emotion from Gross & Levenson were 'amusement', 'anger', 'contentment', 'fear', 'sadness' and as a control 'neutral'.

We pulled a range of videos from each category and arranged them into a slideshow. In between each video clip, the screen was black for 15 seconds, to allow participants to clear their mind of emotions, thoughts, and memories, to reduce the overflow of emotion between videos. In Gross & Levenson's original study they used 20 seconds to separate the videos, but a faster turnover seemed appropriate due to the faster pace of content on social media and other forms of media comparative to 1995.

Participants were shown as many of the 8 videos as time allowed in the following order; cafe scene from When Harry Met Sally (Amusement), police abuse protesters from Cry Freedom (Anger), a tropical beach scene (Contentment), child crying over death from The Champ (Sadness), color bar screen test (Neutral), boy playing in hallway from The Shining (Fear), waves crashing on a pebble beach (Contentment) and mother deer dies from Bambi (Sadness).

After each video, users were verbally asked:

1. Have you seen the clip or film previously?
2. Reflect on the emotions, memories, or thoughts the clip elicited.

Participants were asked their positive and negative affect via the tablet survey after all videos had been seen, which is possibly indicative more of the final video that the participant saw than their overall affect during the task.

The final task in the study was the repeat of the PASAT, either with our without the device (depending upon the participant's randomized order).

After all tasks were completed, participants provided written feedback followed by verbal feedback regarding their fidgeting behaviors and their response to the ball design. We asked participants to compare their usual fidgeting to their usage of the ball, asked if they would use the ball again, and asked for their thoughts on the design of the ball and recommendations for how to improve it.

During tasks where the participant was in possession of the ball, the researcher would enable data capture through the ball. Video and audio were captured throughout all 4 phases of the procedure. Debrief surveys were acquired using Google forms.

5.4.4 Video Coding

To qualitatively characterize fidgeting behavior, 2 coders organized video into 5 categories:

1. Twirling, rolling, throwing
2. Petting, rubbing, tapping the surface of the ball
3. Scratching, digging at the material
4. Pinching,squeezing of the ball
5. Repetitive clicking

Any behavior that did not fall within those 5 categories also got cataloged, to examine if the ball design might need alteration to accommodate the behavior. Once the 5 categories were agreed upon, coders found an inter-coder reliability of 75% over the course of 3 videos before they divided up the remaining videos for coding. Behaviors were measured over 3-second intervals; if the behavior continued past the 3-second period it was counted an additional time. This continued until the instance of that behavior stopped or morphed into another category.

Our categories include several behaviors each, as they were found to be difficult to distinguish easily. Twirling, rolling, and throwing of the fidget ball were amalgamated into one group, because some participants utilized more of their space to fidget with the ball when engaging in these movements than others. In future this behavior could be detected with the integration of a gyroscope.

Petting, rubbing, and tapping were combined into one group, because these fidgeting behaviors involved lighter interactions with a larger section of the surface of the fidget ball. Scratching and digging at the surface involved targeted repetitive medium pressure on a small area of the ball's surface. This category is difficult for the sensors to detect unless the user happened to pick the spot directly above the sensor. Pinching and squeezing was combined into its own category, because it is the heaviest type of interaction with the surface of the ball that did not involve buttons, and often entailed significant pressure. Clicking was easily coded by sound. The behaviors that did not fall within those categories were thrown into the group of 'unique interactions'. These unique behaviors allow us to explore unplanned interactions and understand what additional sensors might help us better categorize future interactions.

5.4.5 Results

Due to data loss during the PASAT test in one or both of the task recordings, only 17 of the 23 participants had complete sets of data. Of that 17, 8 were presented with the ball in task 1 and not task 4 and the remaining 9 were given the reverse condition. Participants consistently did better on the second viewing of the test, with 89% of participants improving on their score from task 1 to 4 reguardless of having the fidget ball.

For those that received the ball in task 1, the mean improved by 3.6 points from 50.8 (standard deviation of ± 6.2), to 54.4 (SD of ± 3.5). For those that received the ball in task 4 instead, their mean improved 4.1 points from 53.4 (SD of ± 6.7), to 57.6 (SD of ± 3.5). The maximum score possible was 60 and of the first group 37.5% (3 of 8) got within 3 points of the maximum on their first try. In the second group 44.4% (4 of 9) of the population got within that same 95 percentile. As a result, we predict that some improvement was stifled by a ceiling effect. In addition, the population size was not large enough to determine significance between the groups; a larger sample size with a more difficult version of this test is needed to determine if this trend holds generally.

During the reading comprehension test (task 2), only 2 participants managed to complete all the prompts within time (98 prompts were provided), one in each condition. 12 participants did this task without the ball, 42% (5 of 12) reported that English was not the primary language spoken at home. Of the alternate condition 36% (4 of 11) reported that English was not the primary language spoken at home. The mean for those without the ball resulted in higher scores than those with the ball, with a high standard deviation in all categories.

We are reporting raw scores as all participants are of similar age (18-35) and education level (some college education) with a maximum possible score of 98. Those without the ball whose primary language was English scored a mean of 77.7 (SD of ± 13.9), of that same group where English was not the primary language spoken at home, they dropped to 74.2 (SD of $\pm$ 6.6). Of the opposite group those that had the ball and spoke primarily English at home scored 69.4 (SD of $\pm$ 16.7), those that did not scored 58.25 (SD of $\pm$ 13.63). It's interesting to note that within our subjects that had the ball during this task, we had 1 participant in the non-ESL and ESL groups that scored below 50% of the answers to this task. Eliminating those two outliers raises the mean of the groups to 73.2 (SD of $\pm$ 15.1), and 65.67 (SD of $\pm$ 5.3) respectively. This wide margin suggests that this test is the right difficulty. There is a slight trend away from those using the fidget ball, suggesting that the ball may be more distracting for this type of task. Again, the population size is not large enough to pull significance from the pilot study.

Due to partial data loss on 7 participants, we only coded 17 of the 23 participants' fidgeting behavior. After coding and quantifying the behaviors, we noticed that of our 17 participants, 5 were particularly frequent in their fidgeting in comparison to the other participants. When counted with the other participants, we found that in all categories the frequent fidgeters increased the cumulative count by 45-78% within their category.

We also found that 7 of the 17 participants had less than 30 codifiable behaviors cumulative over all 5 categories recorded throughout the hour, meaning that 59% of participants were contributing 96% of the total fidgeting. When divided between the categories, we can see that there is a preference within the general fidgeting population toward pinching and squeezing the ball. We did exclude a single user that had 301 instances in the Pet/tap/rub category within their hour session from our analysis as a significantly large outlier (see Table 5.1).

Visual count of interactions					
	Roll	Rub	Scratch	Squeeze	Click
'General' Users (5)	184	118	64	335	48
'Frequent' Users (5)	154	296*	66	327	100
'Infrequent' Users (7)	10	43	8	24	0

TABLE 5.1: Manual count by video coders. Note that within each category participants had multiple ways of performing similar actions. *Note: An abnormally large outlier was subtracted from this category as they had 301 instances of rubbing/petting the ball.

As noted previously, while forming the coding bins, we found that the ball was able to catalog many of the bins, but could not directly detect rolling or throwing of the ball currently, and might have difficulty detecting scratching or digging at the surface, due to the localized nature of these two actions. To better distinguish these two activities in future iterations of the ball we would incorporate a gyroscope to detect instances where none of the sensors are compressed but acceleration was detected. We could also create a field of conductive fabric around the surface of the ball to better detect localized pressure, but this might alter the feel of the ball's surface. We could instead choose to create a localized zone that encourages digging behavior at a point in the ball.

After the participants had completed their tasks, we asked them four follow up questions about the ball itself. We asked participants to compare their usual fidgeting to their usage of the ball, if they would use the ball again, their thoughts on the design of the ball, and recommendations to improve the design of the ball. 9 participants of 23 reported noticing the ball frequently during the tasks, however only 2 of 23 report getting distracted by the ball frequently during the tasks.

When asked what purpose the ball served during the tasks 12 participants answered it served no purpose or it was "just something to hold onto", while another 9 participants expressed sentiments like: "it felt safer to do things, like there is someone with you". When asked if they regularly fidget with items only 4 of the 23 participants answered no, while most participants mentioned they fidgeted with their hair or pens or things readily at hand. When verbally asked about the ball's design, participants were positive about the ball: 17 participants responded that they enjoyed working with the ball, in particular 5 participants remarked on the squishy nature of the rubber skeleton. 3 participants thought the clicky buttons were really pleasant to play with and requested more, and 2 participants liked the surface texture. When asked about aspects they'd like changed to improve the ball, 7 people commented that they'd prefer a smaller version of the ball, 3 people commented a different material as the cover would be more pleasant, and 2 participants commented it would be more pleasant if the ball didn't have a wired connection.

5.4.6 Data Logs from the Ball

While analyzing the data we collected from the user test we quickly realized that aligning specific instances of fidgeting from the video with data from the data logs was possible, but prohibitively labor intensive. The reverse procedure was more difficult, suggesting that the ball was absorbing more detailed information than was detectable via video. For an example see Figure 5.7 which shows a 2-second interaction. It quickly became apparent that hand tagging the gestures from the sensor data would be monumental.

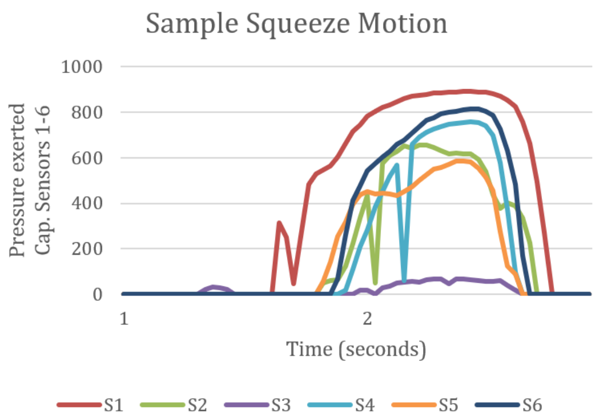


FIGURE 5.7: A sample reading from the 6 capacitive touch sensors over a 2-second period. This series is generated by a 2-handed squeezing motion and activates all 6 sensors to various degrees, sensor 3 was in the palm of the stable hand and was barely activated.

We collected 45 minutes of fidget ball data (appox. 90 samples per second) which resulted in approximately 650 MB per participant, or almost 15 GB of fidget data across all participants that provided complete data sets. In addition to this fidgeting data, we also collected about 45 minutes of video and audio data per participants (recorded and transcribed in post), or about 17 hours of video for a full 23 participants. This mass amount of data is difficult to handle but given an annotated data base our ML partners should be able to create a more streamline analysis tool to help address the sheer quantity of data.

5.4.7 Discussion

When we first started the user test we asked if our design was multipurpose enough to allow participants to actively engage in a range of fidgeting behaviors and if so, would the ball be able to track those touch traces? From a high level evaluation the answer seems to be a qualified yes. While not every participant performed actions in every behavioral coding bin (captured via self report, video coding and touch traces), participants did explore the surface of the ball through squeezing, pinching, petting and using the click buttons. Our team did observe participants rolling the ball back and forth on the table or between their hands and those instances were traceable through surface pressure, however when participants threw the ball into the air touch traces were lost. One participant used the ball to gesture with waving it back and forth without adjusting their grip on the ball, Figure 5.8. In future we may need to incorporate a gyroscope into the interior of the ball to detect such actions.

We also asked if our ball could help ascertain the benefits of fidgeting alongside cognitively demanding work? The answer to this question is less clear, as our

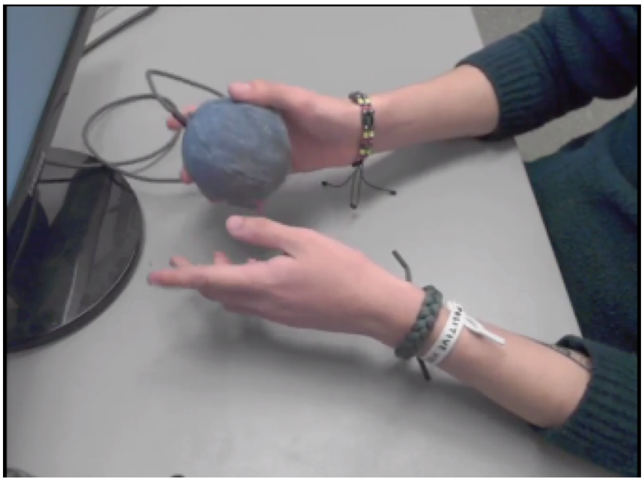


Figure 5.8: A participant waved the ball around while describing an experience, their grip did not adjust and no change showed on the pressure sensors but a gyroscope could have shown motion.

data set did not provide definitive results. We may have hit a ceiling effect and our user pool may be a mix of users whom fidgeting helps and those that it does not. We are working with our cognitive psychologist partner to explore how we might adjust the current tests, and also, how ADHD participants might perform in relation to neurotypical participants.

While we did in fact collect information on patterns of fidgeting, at this stage it is difficult to provide feedback to the user at this point as the data logs do not lend themselves readily to hand coding or traditional statistical analysis. However, we believe a machine learning approach could be a promising way to make use of the rich dataset the sensors provide.

In our preliminary studies, we were able to collect a rich body of fidget traces that lend themselves well to machine learning, and ultimately, to connecting fidgeting styles with directed stimuli. With our instrumented fidget device, we have added a new dimension to fidget behavior observation that can enable more fine-grained understanding of the link between fidgeting and cognitive and emotional self regulation. While our current corpus is not sufficient to easily interpret emotional states from touch, we have shown how machine learning can help interpret fidgeting data without the need to manually code actions based on external observation.

The current version of the deep learning network is trained only to communicate affect based on textual input. If trained with additional tagged content, it should be possible to adjust the algorithm to recognize input from the ball for:

1. Gesture recognition (squeeze, stroke, pinch)
2. Response monitoring (assessing affective response to stimuli)
3. Performance prediction (impact of touch content on concentration)

Eventually this work could be extended to facilitate tailored reactions to help scaffold self-regulation interventions, supporting a positive concentration cycle and providing support to users feeling stress or anger with the task at hand, provided the ball lends itself to the desired manipulation.

We set out to create and test a smart, soft-bodied fidget device for use as a research instrument, to help study whether fidgeting with objects can enhance concentration and help to regulate emotion. Our design was versatile enough to capture a wide range of prompted and spontaneous actions. It also supported a wide range of affective touch behaviors (prompted in study 2). While it seems our device needs some adjustments (such as adding motion detection), its simple design makes it modifiable to suit a broader range of interactions as we continue our research.

5.5 Sensor Remapping and Motion Detection

Our initial data did not show improved cognitive performance alongside fidgeting, we believe a part of this was due to technical errors. Additionally participants were observed to gently toss the ball between hands, which is not captured in the current device. A gyroscope would help capture that action. Participants were also very gentle in their petting motion. I wanted to address both of these issues before additional testing took place so that moving forward we could avoid any other major revisions in the design.

While performing data analysis with the ML team, collaborator Dan Shapiro noted that since we had 2 different physical models of the ball and we were trying to create one ML model from the two devices it was important to note the orientation and position of the pressure pads which when assembling the devices was not accounted for. As a result we needed to come up with a standardized map for sensor location in future which could also help create known orientations for the gyroscope and other components rather than placing them in a distributed but semi-random placement across the devices surface.

Based on feedback from both users and the experimental team, alongside failure points I revised the prototype to include the following changes:

1 A more flexible/stretchy USB cable as the previous cable kept getting stressed at the connection point

2 A fully described map of sensor locations for duplication reliability and ML coordination

3 A gyroscope for orientation description

4 3 mechanical buttons that are robust enough for repeated usage by users

To ensure that the pilot results were still reliable we kept the user facing heuristics consistent. We mapped out the geometric surface and plotted out usable locations that would distribute the sensors under user's hands (assuming the USB cable was facing away from the user, such that they were oriented toward the opposite pole). For final sensor placement please see the sensor map Figure 5.4. The new model should help keep consistent data flow no matter which device is in use. Additionally software was updated to modify the collection process to create a CSV file as the text files that were previously collected were difficult to parse.

A typical data stream in the Arduino serial monitor looks like figure 5.9, which if we examine more closely and insert artificial gaps in the data we can parse a little easier (see 5.1).

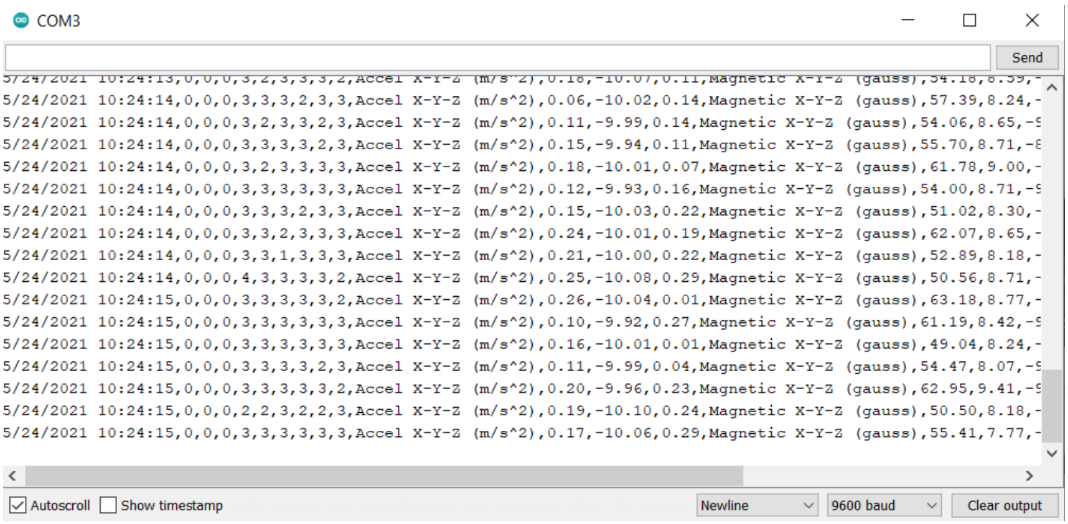


FIGURE 5.9: Fidget ball data stream.

$$
\begin{array}{ccc}
5/24/2021\ 10:24:14, & 0,1,0, & 3,873,2,245,3,3, \\
|--Timestamp--| & |Click\ buttons| & |Pressure\ sensors| \\
(Down\ to\ Sec) & (0\ or\ 1) & (0\ to\ 1023) \\
 & & \\
Accel\ X-Y-Z\ (m/s^2), & 0.60,1.64,9.63, & Magnetic...\ etc. \\
|----------- & -GyroscopeData- & -----------|
\end{array}
\tag{5.1}
$$

The first group of numbers is the timestamp, while our timestamp only measures in seconds, our program is speedy enough to retrieve 9-11 data points per second when handled in sequence according to coming into the recording program this can show millisecond level detail of when a user started interacting with the ball.

The next 3 digits are the mechanical 'click' buttons, 0 is not clicked, 1 is clicked. These are arranged so that the outside button that's part of the pair (furthest from USB cable) is the 1st output, the middle button is the 2nd number, and the solo button (closest to the USB cable) is the 3rd number.

The next 6 numbers are the capacitive pressure sensors, used to check when the surface is being touched, they range from 0-1023. In general readings below 20 is no pressure, holding it in your hand or resting on the table is about 300 and heavy pressure reaches about 700-900. It should be noted that if the fabric skin is too tight it's possible for a false constant reading of more than 100 without pressure applied, this can be solved by plucking at the surface of the ball a little to re-seat the material. Additionally the ball resting on the desk can exert some pressure which might cause some false positives.

The final block of text is the gyroscope, this is the most robust of the sensors on the device. The gyroscope triplets (each is 3 axis) are within the same microchip and are strongly linked to each other so we'll see correlated changes as the ball rotates (compared to the click buttons or pressure sensors which are dissociated from each other).

The accelerometer measures in meters per second squared (m/s^2) and is currently set to top out at either + or - 16 g (1 g is 9.8 m/s^2 so 16 g would be 157 m/s^2). Magnetometer is basically a 3 axis compass and measures in Gauss, it maxes out at 1916 before it wraps around to -1915. Anything above 1850 or below -1850 should be suspect. This is the least useful of the three measurements as most computers and laptops have some sort of magnetic field so this is going to be wildly variant between participants depending on if they have a wrist device. Finally the gyroscope measures angular velocity in Degrees per Second. It's min/max is currently set to +/- 2000 dps but this could be adjust with software if more detail is needed.

In both versions of the ball we kept the external design intentionally neutral (to avoid unnecessary bias), creating a secondary version of the ball with a variety of material properties could elicit more specialized touch interfaces. For the time being however, the primary focus for users should remain on the provided stimuli with the ball acting as a conduit for expression rather than the focus.

5.6 MIND Institute Fidgeting Effect Study

Having completed initial pilot study of the baseline population, we began working with Julie Schweitzer from the UC Davis, MIND Institute to examine fidgeting behaviors in people with ADHD. In July of 2020 we successfully obtained a 2-year grant from the National Institutes of Health to perform a much larger scale user study, with stated goals to explore 4 research questions:

RQ1 Does fidgeting regulate attention and emotion in adults with ADHD?

RQ2 Does fidgeting change cognitive/affective state or express it?

RQ3 Does the content and sequence of fidgeting behavior matter?

RQ4 What characteristics of touch are involved?

Demographics: This study will run 100 participants through 2 conditions, either with or without the fidget ball. All participants will be people who have been clinically diagnosed with ADHD.

Procedure: Participants will be run through the PASAT, followed by the Flanker task, an attention driven task where users are shown a sequence of arrows on screen, participants have to respond with the correct direction and their response time is measured in millisecond alongside accuracy. Participants will then be shown an abbreviated version of the emotion induction film sequence, followed by the Trier Stress Test (TSST), where participants are given a short amount of time to prepare a public speech that they're told they will need to present.

Equipment: In addition to using the third iteration fidget ball, participants will also be equipped with body sensors for data gathering: a Heart Rate Variably sensor, Cardiac impedance, and 2 accelerometers (ankle and wrist). Similar to my pilot test, participants will be video taped to complement the sensor traces and identify fidgeting gestures from video. Previously we used power point and 3 different programs to collect data from the user, however the test stimuli will be coordinated through ePrime, a testing platform that is well known in the psychology field. As a result of my pilot study we've been able to maintain the previous behavior categories for future video coding rather than starting from zero.

5.7 Delays and Contributions

Unfortunately the Fidget Ball project slowed down significantly after the second user test. I had initially intended to run a follow up study with the neurotypical user population before Julie's team got going but the campus was shut down due to graduate student union strikes in late Winter Quarter 2020 and by the time that had wrapped up the global COVID-19 pandemic had caused the campus to close with little indication of when it would reopen. I attempted to restart my procedure in Fall quarter 2020 when it looked like the case numbers in Santa Cruz were steady enough that the administration would allow in person research however due to a spike around Thanksgiving, that was quickly dismissed.

Instead I spent my time helping the UC Davis team assemble their materials based off of my experience with running my pilot study. I helped streamline the emotion elicitation videos so that they were shorter, more current clips, I helped implement data structure changes to the fidget ball code to help integrate with their software and reformat the data to more easily be exported for ML training. Additionally I've assembled multiple devices for rotation and maintenance purposes so that once the user study begins they can exchange faulty devices in time for repairs.

Chapter 6

Contribution and Possible Future Work

6.1 Summary of Contribution

In this dissertation, I have described my work on two deformable controllers with built-in sensors and touch trace storage, both aimed at supporting self-regulation. Taking a Research through Design approach, I developed appropriate affordances and underlying technology in close collaboration with interdisciplinary teams, making an RTD contribution to the space of smart devices to support self regulation. The SEL animal prototype was validated with the target population and was translated into a commercial device. It also resulted in the development of the intimate-space social robot concept, which is a contribution back to the research community.

The Fidget Ball has served as a proof of concept of the possibility of capturing and analyzing touch traces with such devices using machine learning. It is also presently being used in an NIH-funded research study aimed at investigating the benefit of such devices to support attention regulation in people with ADHD.

Overall, my dissertation research has helped to define and refine the space of deformable controllers that capture and respond to touch traces, to support end users' emotional and attentional self-regulation.

Let's now re-examine my core research questions:

1 Can we design an intervention tool that helps improve the user's ability to self regulate?

2 Is it possible to detect a person's attentional or emotional state via their interaction with a tangible interface?

3 Can we provide timely feedback that helps the individual self-regulate?

The SEL device supports a positive answer to the first question; the Fidget Ball work is still in progress. Regarding the second question, our research with the Fidget Ball does support the notion that we can detect a person's emotional state via interaction with a tangible interface. Finally, the SEL device's haptic-based interactions did provide timely feedback that helpd the individual to self-regulate. In the long run, I hope that future researchers will be able to use touch traces from these devices in order to tailor interventions and to support communication between caregivers and end users toward helpful support of attention and emotion management.

At present, work is continuing in both streams of research. Petr Slovak and his team are using the commercial SEL creature to conduct studies with various populations, and the UC Davis ADHD-related study will begin this summer. I'm proud that my dissertation work has resulted in impactful contributions to two intervention areas–supporting children's emotional regulation, and investigating the value of fidget objects in regulating attention for people with ADHD. I also hope that the contribution of the intimate-space interaction with SARs will be of value to the HCI and HRI research communities.

6.2 Practical Recommendations

A few key practical observations stand out that another researcher looking to dive into creating deformable controllers might find useful. One key consideration is washability. I've had a number of discussions with my cohort about lasting designs that are child safe, soft-bodied and washable.

A number of researchers in the TEI community choose to avoid the issue by creating exemplar designs that they keep for demonstration purposes, which are filed away otherwise. In these cases, field testing for any period of time is out of the question. In the case of the Anxious Creature field test version, we did something along these lines, in that we kept one on hand for demonstration purposes (as well as a second one as a reserve in case we needed to swap out a field model that was broken).

Our primary method of washing the toys was to wipe them down with baby wipes, but you can imagine that this is less viable long term if the toy gets something spilled on it. The Purrble found a nice balance where they limited sensor locations and thus allowed for the removal of the electronics for a quick trip to the wash. For the fidget ball, since the fabric skin is fairly simple to make, once it gets a little matted from usage (typically after 10-15 user tests) I'd take the stitches out and replace it with another cover. Alternatively this could be done with a zipper or some other sustainable method. This became of increasing interest as we moved into the COVID-19 pandemic when it was still undetermined exactly how the virus spread and what surfaces were more or less prone to transmission. Consider cleaning methods when you create your devices and carefully decide if the sensor needs to be stitched in, or if it can be placed within a pocket for easy removal and installation.

Along these same lines, it is helpful to make sure your sensors are modular for easy replacement. I found myself having to solder more than a few sensors throughout the course of my projects and there are only so many times you can do that before your micro-controller (MC) itself gets to be a bit of a mess. I'd recommend affixing your sensors to either female socket headers so that you can detach your sensors from the MC before soldering, or develop a separate daughter board that allows you to attach individual sensors by sockets rather than having them on one attachment point. This allows you more flexibility in replacing dead sensors, but comes with the added question of making sure the sensors stay connected to the MC.

Speaking of flexibility, I highly recommend using silicon coated strand wires rather than single core wire, as the silicon coat allows the wires to move around as the device is deformed and the sensors are less likely to take damage from repeated usage. If the attachment point is floating (like we had in the ears and the feet of the Anxious Creature) you can stick the sensor through a piece of foam or into another soft medium before soldering on the wires and this will help deflect pressure away from the attachment point and give you something more to hang onto when trying to position the sensor in the device. Alternatively if your positioning something over the top of free floating strut like we hand in the fidget ball, I'd recommend bulking up the strut with hot glue, rubber bands or extra yarn to make sure that the sensor is going to stay where you want it rather than just using pressure to will the sensor into place. We had quite the issue with the fidget ball sensors moving around while being used by the frequent fidgeters and need to reinforce the attachment points so that the wire connections held up.

If you can make your electrical design flexible and modular, that should help with creating an exterior that is washable. As far as fabric-embedded electronics, this I think is going to be the next big hurdle for smart deformable devices. This area is rich with possibilities, but most devices in the maker community are shown within a very short period of time before corrosion has become a problem, so trying to make stable prototypes that stand the test of time remains an interesting challenge problem.

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