Visuospatial Assistive Device Art: Expanding Human Echolocation Ability

March　２０18

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Abstract:

This study investigates human echolocation through sensory substitution devices for the augmentation of visuospatial skills, thus replacing vision through acoustic and haptic interfaces. These concepts are tested through two case studies; *Echolocation Headphones* and *IrukaTact*. The *Echolocation Headphones* are a pair of goggles that disable the participant's vision. They emit a focused sound beam which activates the space with directional acoustic reflection. The directional properties of this parametric sound provide the participant a focal echo. This directionality is similar to the focal point of vision, giving the participant the ability to selectively gain an audible imprint of their environment. This case study analyzes the effectiveness of this wearable sensory extension for aiding auditory spatial location in three experiments; optimal sound type and distance for object location, perceptual resolution by just noticeable difference, and goal-directed spatial navigation for open pathway detection. The second case study is the *IrukaTact* haptic module, a wearable device for underwater tactile stimulation of the fingertips with a jet-stream of varying pressure. This haptic module utilizes an impeller pump which suctions surrounding water and propels it onto the volar pads of the finger, providing a hybrid feel of vibration and pressure stimulation. *IrukaTact* has an echo-haptic utility when it is paired with a sonar sensor and linearly transposing its distance data into tactile pressure feedback. This gives users a quasi-parallel sense of touch via a cross-modal transaction of visuospatial information that enhances their ability to gauge distances through touch. *IrukaTact* has assistive capabilities for vision in aquatic environments where it is difficult to see. Similarly, the *Echolocation Headphones* have assistive capabilities for participants who may already depend on audition for spatial navigation and object location. These devices are an example of cross-modal Assistive Device Art (ADA) which expand the visuospatial skills and experience of human echolocation. This kind of art derives from the integration of Assistive Technology (AT) and Art, involving the mediation of sensorimotor functions and perception from both, psychophysical methods and conceptual mechanics of sensory embodiment. These cases are examples of deploying this new framework of Assistive Device Art, tools with an assistive utility to embody new perspectives and gain new skills.

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1. Introduction

This thesis introduces a conceptual framework, Assistive Device Art (ADA), by which to define, produce, and evaluate tools that expand human sensorimotor abilities with the aim to facilitate experiential awareness about the diverse perceptual mechanisms that lie on the wide spectrum of human skill and ability. ADA derives from the integration of Assistive Technology (AT) and Art, involving the mediation of sensorimotor functions and perception from both, psychophysical methods and conceptual mechanics of sensory embodiment. ADA seeks to augment the functionality of electronic displays by adopting AT as a guide for designing new sensory interactions in computing interfaces. This concept engages a broader audience as users of AT with the aim to expand their perceptual acuity towards alternative methods of sensing information. AT is a rich reference model for designing innovative interfaces; this field harnesses a fruitful potential for the future of Human-Computer Interaction (HCI). ADA tools adopt AT functionalities and integrates them into desirable products, reframing this technology from aiding disability into adding super-ability, thus embracing atypical physiology as an inspirational source of diverse sensorimotor architectures. This empathetic approach towards tool design evolves the aesthetic and cultural associations of AT giving rise to a new user base motivated by curiosity and willingness to playfully engage in an alternative perceptual experience.

In this research study, we use two ADA sensory substitution devices that translate vision into audition through the *Echolocation Headphones*, and somatoception via *IrukaTact*, to test the visuospatial abilities of participants with no visual impairments. Visuospatial ADA tools increase sensory skill development via substitute perceptual architectures that re-channel a user's attention from one sensory modality to another, in this case, their visual scope into their audible or tactile reception. This sensory input substitution is possible because visuospatial awareness is a multimodal precept. It is an ability informed by a multitude of senses that include vision, audition, somatoception (touch), and most importantly, proprioception. The latter is the sense of knowing where we are in relation to our environment and ourselves. By devising two case studies that refocus a participant's spatial awareness to audible echolocation via the *Echolocation Headphones* or as tactile transposition via the *IrukaTact* searching tools, this research examines specific cross-modal connections within our visuospatial system. These case study interfaces have been designed and tested by applying the ADA tool design framework. This investigation has an interdisciplinary approach that involves both scientific and philosophical points of view, incorporating psychophysical and interaction design principles for tool design and evaluation.

The ADA framework bridges the gap between disciplines, borrowing from an aggregation of viewpoints to reflect on what constitutes skill and ability as it co-evolves with technological prosthetic extensions. This interdisciplinary approach involves theoretical models from HCI, sensation and perception science, and philosophical inquiry, incorporating principles such as psychophysical evaluation, experiential interface design, and artistic conceptualization and presentation. The HCI field has well-established methods that place the user at the center of the system. The ADA framework dislocates the idea of a user by re-setting the purpose of assistive utility and instead these tools serve as a means to engage in experiential performance. The user is a performer augmented and co-adapting with the interface. In the scheme of an ADA tool, the principal motivation is to display a distinct sensory architecture that the participant slowly absorbs with practice and attenuation. This process of tool incorporation enhances their understanding of what constitutes skill and ability. ADA engages participants in technologically aided disability performances that form new constructs physiologically, intellectually, and socially through the means of relational empathy. ADA tool design centers on experience, it seeks to explore of the limits of our perceptual abilities by adopting new models of observation. Furthermore, this research investigates how the rising interest in sensory pliable wearable computing devices could earn a broader and more inclusive consumer demand base for AT. Current tools that provide alternative avenues for perceptual display are meant to fill a need in the sensory impaired community, thus existing as accessibility devices. These devices provide a way for them to supplement their abilities while performing daily tasks and correct their physiological disparity. ADA looks at AT as a model from which to derive alternative information displays that further the status quo of interactivity. The ADA framework seeks to sway attitudes toward ability via experiential models that fashionably facilitate assistive awareness.

This research broadly explores the extent at which humans are willing and desire to integrate with computing interfaces. It questions how AT could be adopted for conventional device design not only for socially integrative purposes but rather for the further development of richer digital experiences created for the multimodal palette of human perception. In the case studies section, this study assesses the functional viability of two specific ADA tools through a series of psychophysical experiments that evaluate the performance of visually able participants engaging in spatial tasks while deprived of vision and instead, wearing visuospatial translating ADA tools. Given that the majority of device displays are centered on vision the focus of this study is to learn how to supplement visual information, and as for this particular study we focus on visuospatial tasks. Through these tests, we examine how successful the participating subjects were in accomplishing visuospatial cross-modality. We consider that non-visual spatial perceptual abilities may be more natural to visually impaired people who are able to process mental imagery. If their physiology is accustomed to use audio and somatic cues in order to perceive spatial information, they would therefore have a perceptual advantage above sighted subjects who are instead accustomed to perceive visual phenomena and so imagine spatial information with visual quality. This research takes into consideration the public dialogue caused by the portrayal of ADA as potential or real commercial products through the media. It also analyzes the public reception of ADA tools via artistic dissemination by presenting these prototypes as artworks and collecting feedback from exhibitions via interviews and observation. This research concludes by extracting the essential aspects of ADA and how it relates to the future of wearable computing, honing in on the importance of perceptual diversity and cross-disciplinary approaches to tool design.

1.1 The Human-Computer Relationship

> *"With every tool man is*
> *perfecting his own organs,*
> *whether motor or sensory,*
> *or is removing the limits to*
> *their functioning"*
>
> *-Sigmund Freud,*
> *Civilization and Its*
> *Discontents*

All technology is inherently assistive, from a hammer to the mini digital computers we carry in our pockets. The smartphone is a device which has almost become another cognitive human organ, equipped with extra memory and beyond. In the mid 1980's and the early 1990's when the cellphone became a popular commodity, it was a brick like device with a long antenna providing expensive talk services. In 1992 the first Global System for Mobile Communications (GSM) device became available (Temple 2017). It was able to receive Short Message Service (SMS) and looked more like a suitcase than a pocket phone. These devices had limited input and display capacities, most of them only featuring a microphone, a speaker, and passive matrix LCD displays. From an automobile accessory, the mobile cellphone yearly transcended into a smaller and more compact pocket device. The features of today's smartphones are improvements on the same interface design of three decades ago. Their scale has massively changed, but their form still remains a rounded corner, rectangular interface. Along the way of the mobile cellphone's evolution, only a few new interactive features have been implemented, beyond the improvement of quality in screen resolution and portability. The now lost flip-phone design feature possibly came from the interactive link of simulating the action of hanging-up a land-line telephone, or perhaps to simply reduce the size. This feature was discontinued through the years and it was never truly adopted as a user need, since then more people today are likely to relate to mobile phones rather than landlines, and the scale of electronic components has shrunk significantly. One novel interaction design feature that still remains in cellphone designs today was introduced in 1992 by Nokia when they filed the patent "Mobile Phone with a Vibrating Alarm" (A.M. 1992). Adding a weighted motor that vibrates instead of or in conjunction with an audible signal was the first attempt to expand the mobile's sensory display methods. This was the first time for digital haptics to become incorporated into these consumer electronic devices. Haptics and other sensory display methods can provide more realistic renderings of digital display experiences, they can also reinforce signaling and more universal interface designs. Adding novel sensory transducing features to consumer electronic devices demands more attention as these are the forefronts for HCI development.

Today's typical smartphone displays audible, visual, and haptic information, equipped with a full-sized touch-screen, a flashlight, and a speaker. This efficient machine has a myriad of sensors such as a microphone, accelerometer, gyroscope, GPS module, dual front and back cameras, Bluetooth, WIFI and other network radio transceivers. The smartphone helps us orient ourselves beyond the spatial constructs of geolocation. It is a compass that guides our place within society, as they connect us to the rest of the world and are our portals to the internet. The smartphone is a prosthetic command center from which we transmit audio-visual messages and record our memories. They are adopted as a multimodal part of our body giving us extra abilities to connect and orient ourselves. There is no question that smartphones are popular, desirable, and assistive. Perhaps, the rectangular form and screen display interface of the smartphone is another passing feature such as the flip-phone. This device has evolved to become a powerful efficient prosthetic extension.

In these times when we are constantly wondering if technology has sufficiently engulfed us, we ask ourselves how far are we from a machine? After all, we are electric beings. The story about the discovery of the body's electric potentials is closely intertwined with the story of the battery. When Luigi A. Galvani discovered galvanic stimulation, he thought that bodies had an "animal electric fluid" which was different from metal induced electricity. His associate, Volta, did not believe this liquid was particular to animals. Instead, Volta used his friend's name to coin a new term "galvanism" meaning a direct current of electricity produced by chemical action, an idea that shortly led him to invent the battery (Houston 1905). Without the electric circuit that encompasses our nerves, we would not have the batteries that power the vital computing extensions that we harbor in our pockets.

Technology is the human way of coping with the compulsion to manipulate nature; it is an extension of our agency and motives; it's a survival mechanism. Computing interfaces are so omnipresent in our daily lives that they have become virtually synonymous with the term technology. Through the course of our human-computer integration, the form of interfaces has significantly changed, and the fundamental contributing factor to this phenomenon is scale. As computing devices become smaller and more efficient, they further integrate with our physiology. This pervasive incorporation has increased the electronics consumer's appetite for interfaces that provide novel sensory experiences. Electric devices have reached another level of functionality plasticity as electronic components and modules are readily available, and programmatic knowledge is easily accessible. The technical functionality of wearable computing media is fluid and interchangeable; however, interaction and experiential design are the critical defining guides to the extent at which we dip within the virtual.

The miniaturization and wearability of computing devices have also caused an unexpected catalyst between industries, for example, in the convergence of medicine and entertainment. Medical devices that were once costly and only available to doctors as diagnostic tools are now being worn by the average person on their wrist as a fashionable accessory. Wearable devices that track bio-signals such as heart rate, perspiration, and sleep quality, give users a new intimate scope by which to learn more about themselves. Consumers embrace the commodification of a quantified-self, eager to adopt new sensory avenues by which to enhance their physiological mechanisms. Whether to collect innumerable amounts of data or expand their motor abilities, these consumers seek tools that afford them a fuller experience and an ever more encompassing perceptual awareness. The growing interest in biometrics oriented devices is an exemplary phenomenon to the motives that drive innovative experience and interaction design. This eager adoption provides an outlook on the direction in which humans are co-evolving with their machines and reveals the collective, yet intimate, demand for experiential intensification.

This inward shift towards human-aware technology has also influenced the drive for innovation in the area of information displays. The visual representation of information is the primary focus of digital display technology because human perception is highly visual. Scientists estimate that the cerebral cortex dedicates 50% of its processing to visual information (Hagen, 2012). At this specific point in time, we can see Virtual Reality (VR) headsets flooding the markets absorbing teenagers in a virtual environment. Ordinary people glued to their palm-held devices are squinting over a small screen that contains an entire toolkit. It is the Swiss Army knife of digital experience, designed to assist with a myriad of tasks, whether navigational, social, or biometric. Wrist or pocket screens and stereoscopic wearable displays are all examples of the central role that vision plays in digital display design. While the brain is a multimodal organ and its visual mechanisms process many other sensory modalities, very few interfaces have ventured outside of screens and taken advantage of this pan-sensory aspect of perception.

1.2 The Plasticity of the Mind: Sensory Substitution Devices

Neuroplasticity and sensory substitution theories suggest that the brain is moldable and adaptable based on conditional circumstances such as change in behavior or environment (Pascual-Leone et al. 2011). Also known as brain plasticity, this area of study aims to answer one of the most intriguing questions of neuroscience; how does the nervous system adapt its functionality based on sensory input, experience, learning, and injury? (Kaas 1991; Björkman et al. 2011). Plasticity can occur rapidly with an intervention based on decreased inhibition, meaning that the receptive field occupied by a past signal will expand to enable other neurons to be excited by a new stimulus (Sanes, et al. 2000). The perceptual mapping of sensory substitution is more complicated than extending a signal from one neuron to another; it takes practice. Take for example a person who is congenitally blind; they were born without the ability to see. Suppose they only knew objects based on their tactile information. They know what a ball is, as they have touched and played with one before. Imagine that this person suddenly gains their ability to see. They open their eyes and finally see a ball in front of them for the first time. Could they distinguish the ball based on sight alone? This is Molyneux's philosophical problem and it has provoked sensory mapping research since 1688 (Degenaar et Al. 2005) His question was seemingly simple but complicated to answer by postulation alone because in his time there were not many treatments or cures to any kind of congenital blindness. There were a few attempts at experimentation to answer this problem, but they were deemed inadmissible given lack of controlled circumstances. However, Pawan Sinha responded to the question with proper experimentation in 2003. (Ostrovsky, Sinha, et Al. 2006) He determined that the answer to Molyneux's problem is that, in the case of the previous example, the person would not be able to distinguish the ball by sight alone. This is because congenitally blind individuals who suddenly gain their sight cannot immediately relate the visual phenomenological information from the same object they only knew by tact alone (Degenaar et Al. 2005). Instead, the connection between the senses is learned by experience. Pawan

Sinha stated in his research that his subjects were able to create this tactile to visual link within a few days (Ostrovsky, Sinha, et Al. 2006). This means that sensory substitution is a learning process, and not an immediate outcome. The ways in which the brain works to capture and adapt to experience has researchers, neuroscientists, and most people alike incredibly curious.

Paul Bach-Y-Rita was a pioneering neuroscientist in the field of neuroplasticity. He learned about the brain's plasticity as he assisted his father to regain control and recover some of his lost sensorimotor abilities after he suffered stroke that left part of his body unresponsive (UW 2006). Throughout his career, he created successful devices that enabled congenitally blind individuals to gain a new perspective on the world via tactile-vision. He did this by creating a series of devices that transposed visual information to a matrix of haptic transducers. His most famous device was the BrainPort, which consisted of a pair of opaque glasses with a small camera attached to a tongue display unit that induced small electric currents in correlation to the image taken from the camera (BrainPort 2017). This masterful neurological experience device designer shared some of his views on the future paths for sensory substitution prototype development, as quoted below:

> "Research up to the present has led to the demonstration of reliable prototypical devices that use sensory substitution to restore lost sensory function. There are three envisioned paths of future development. First, and most urgent, is the development to robust and relatively inexpensive implementations of the technology to make it accessible to a wide range of patients suffering sensory loss. Second, moving beyond the restoration of lost senses, it should be possible to use the same technology to expand human sensibilities, for example, enabling the use of night vision apparatus without interfering with normal vision. Finally, the technology enables a whole range of non-invasive low-risk experiments with human subjects to gain a deeper understanding of brain plasticity and cognitive processes."
>
> -Bach-y-Rita and Paul, Kercel (2003) on their article "Sensory Substitution and the Human–Machine Interface."

Sensory substitution is not a function of cancelling the properties of one organ and replace them with another. Instead, the substitution occurs by a shift on focus from one sensory pathway to another, and it can be achieved for certain multimodal precepts. Experiences that are rich in phenomenological information can be perceived by multiple types of sensory processes. The combination of HCI and brain plasticity methodologies have provided new types of tools useful for achieving sensory substitution via computing interfaces. These sensory-mixing techniques are applied to inquire on the adaptability of the brain and to translate its perceptive functions. As participants engage with these sensory remodeling devices, they re-channel their senses. Sometimes they retain perceptual agency over the device, and other times, the device overrides their physiological perception of certain stimuli. Some interactions of sensory interfaces are already hardwired, such as bone conduction hearing. Others require training and practice in order to achieve a level of brain plasticity and bio-cooperation. For example, in tactile-sight, the perception of visual information from somatoception requires tactile discrimination which is a cognitive related task (Bach-Y-Rita, 2003). Sensory substitution devices function as training devices until the experiential connection is mapped in the brain.

1.2.1 Towards a Future of Electric Savants

One can assume humans walk upright, talk, and have the possibility to sense in the spectrum of around 430–770 THz of the visible and between 20–20,000 Hz of audible electromagnetic frequency range. These are all normal human abilities, that can be supported by utilitarian technology, but what about talent or disabilities? Are we striving to remain within these capabilities? How will these traits inform the path of our adaptability and HCI co-evolution?

Disabilities are often seen as the disadvantages that a person has in comparison to the average abilities of normal individuals, rather than regarding the specialization of their perceptual abilities. Why should we not refer to deaf individuals as "visually enhanced" or the blind as "sono-somatic" humans? The plasticity of the mind allots processing currency depending on the necessity of specific functions based on sensory ability. Disabled individuals are often seen to compensate their perceptual processes with their abled senses more acutely than any individual with normal physiology, e.g. the heightened sense of hearing in a blind person. This adaptability of the brain to assume more processing power to any of the senses is also present in cases of the savant syndrome.

Although extremely rare, this syndrome occurs in some disabled individuals who, beyond their disability, display "islands of genius" compensating their 'incapability' with strikes of genius in mathematical calculation, memorization, lingual, and artistic abilities among others (Treffert 2005). This syndrome, occurring in one of ten autistic individuals, has been previously described as an "autistic savant" syndrome even though only 50% of people displaying these characteristics are actually autistic. The other 50% of people displaying the savant syndrome are disabled individuals who have sustained damage to their central nervous system either by an injury or a disease (Treffert 2009). This condition can be acquired during a lifetime accidentally or congenitally. According to Treffert (2009) these extraordinary abilities can be acquired and lost in inexplicable instances. Damage to the central nervous system can force the brain to redistribute its processing mechanisms, sometimes resulting in this savant effect. Often, this syndrome is associated with some form of dysfunction in the left-hemisphere of the brain with a concurrent compensation from the right-hemisphere, leading to an affinity for non-symbolic skills (Sacks 2007).

Intellectual capacity is probably the most sought-after ability that humans would wish to enhance. What type of device could safely and temporarily induce enhanced intellectual abilities similar to the savant syndrome without inhibiting other brain functions? Can the savant syndrome be electrically induced by inhibiting the left hemisphere of the brain? Research suggests that it is possible to artificially induce this type of savant state. In his studies, Allan Snyder (2009) argues that these savant skills are latent in all humans. He hypothesizes that people who present these abilities have privileged access to raw, lower-level, less-processed information before it is labeled into holistic concepts. And while all of us have access to this information, it is somewhere beyond the grip of conscious awareness and irretrievable by introspection (Snyder 2009).

There are various types of transcranial stimulation, these are methods by which to artificially induce or inhibit cortical excitability. Most commonly used are transcranial direct current stimulation (tDCS), and repetitive transcranial magnetic stimulation (rTMS). While these methods of cortical excitability require applying magnetic fields or electric currents to the brain, they are relatively low frequency fields and weak currents. They only virtually affect the normal brain functions for the limited time in which these are applied and sometimes only lasting a short period of time afterwards. It has been found that for the case of tDCS an anodal stimulation enhances cortical excitability, while cathodal stimulation inhibits these (Nitsche et al. 2003). Transcranial stimulation has been used to study many of the brain functions, allowing researchers to selectively stimulate cortices and gaining new insight on how specific mechanisms operate. For example, this method has helped patients that have damage to their motor cortex to regain some motor control functions (Nitsche et al. 2003). Naturally, both tDCS and rTMS methods have been used to artificially induce similar cortical activity networks to those who exhibit the savant syndrome. The USA Air Force has applied the tDCS method on some of their soldiers as they engaged in drone guiding simulations. The application of 2mA direct current for 30 minutes to the left-anterior temporal lobe has been shown to shorten the training time of these soldiers in half (Nelson et al. 2016).

Beyond the applications of electric savant inducing technology for research purposes, a group of Michigan hackers created the *GoFlow* (2012). A simple tDCS instrument with two electrodes connected to a 1.5V battery. This technology is so simple that if it was found to be completely benign and augmentative, it could one day become a required school supply. It is open-source and available to anyone. However, there is not enough conclusive information about the long-term effects induced by tDCS. It should be noted that interfaces that apply electricity to the body are considered non-invasive because the device itself is not implanted within the body. This type of AT is assistive to humans with normal abilities by disabling their normal functions inhibiting some abilities to induce others. Systems such as the *GoFlow* have the potential to further natural human ability by presenting a curious dilemma, while we gain new abilities often times it is at the expense of another. The phenomena of electric enhancement to the body may make some forms of disability desirable. At which extent are we willing to modify our bodies to incorporate technology that while enhancing us they temporarily disable us? How can we gain new sensibilities without the danger of loss? Human adaptability is guided by a technological co-evolution. HCI guides the balance between the switches that add and/or subtract human abilities, and as it tailors our bodily extensions, it should be crafted with careful consideration of by which extent it is assistive or disabling.

2. Principles of Sensory Perception

The performance of being and becoming is drawn by intuition, which goes beyond the synthetic a priory and the spectacle view of reality. The fabric of our experience is a malleable control station that manages spiraling inputs and outputs in between the synthesis of our reality. These signals are interpreted as a map, a direct imprint of our interactions with the surrounding environment, of where we are and how we are. This mass of knowledge and structural material, consisting of directions and pathways that direct us in a loop of empirical information, memory, and deduction are the lenses of perception. The a priori structure of organizing thought and sensory data, is spatiotemporal in nature (Brook 2016). The a priori structure of the mind is an imprint of the jewel of our environment, the schemata by which we draw our intuition. (Stearns 2014, LAO 2017).

Traditionally we learn about the five senses vision, hearing, touch, smell, and taste as unimodal experiences. However, increasing evidence in the fields of psychology, psychophysics, and neuroscience suggests that the brain is a multisensory organ. Organisms have specially calibrated anatomical receptors extending to the periphery of their neural network. The fundamental bio-receptors classify into three main categories: photoreceptors which perceive light, chemoreceptors which sense chemicals, and mechanoreceptors which are sensitive to vibrations. These anatomical mechanisms are the essential structures that give rise to the complex systems that we understand as any given sensory modality. Each receptor has evolved to receive specific energy variations from its environment. Organs such as the eardrum slowly developed as a small part of the larger auditory nervous system from a lengthy process of adaptation and fine-tuning to the specific needs of human hearing. Mechanoreception is the ability to detect and respond to touch, sound, and changes in pressure or posture. The primary physical need to detect movement or any other environmental signal arises from the same evolutionary purpose of developing a physiological strategy for survival, an ability to respond to the signals of the environment. Most organisms have some form of mechanoreception, in humans hearing and touch are both forms of detecting force, movement, and vibration. Some organisms co-adapt their sensory system to the same signals emitted from the environment, as humans are not the only organisms that can hear sound. Other species such as elephants have more sophisticated infrasonic detection mechanisms, able to sense a much lower frequency range than that of humans. Generally, organisms have multiple receptors that are complementary to their particular physiological requirements and niche habitats. They sense a whole range of vibrations from their surroundings, absorbing a myriad of information streams in their periphery, while selectively synthesizing the convergence of these signals. As signals become coherent either by spatial, temporal or isomorphic direction, the sensorimotor mechanisms adjust their attention in synchrony to the relevant signals. There are no organisms in the animal kingdom that have complete separation of sensory processing (Stein et al. 1993). The coordination of the senses is the very mechanism that allows for organisms to meaningfully interact with the environment as well as attend to their own physiological needs. Extensive research has been done about the specific sensory receptors and their specific driving mechanisms; however, it is still not clear how the processing of these signals occurs.

2.1 Multisensory Integration

According to Driver and Spence (2000), most textbooks about perception are written by separating each sensory modality and regarding them in isolation. However, the senses receive information about the same objects or events and the brain forms multimodal determined percepts from a variety of informational inputs. After the 1980's perception researchers began acknowledging the importance of studying the interplay of between the components of the sensory system network is equally important as understanding these modalities in isolation (Driver, Spence 2000). Multisensory integration is the process by which information from different sensory modalities are combined to form perception, decisions, and overt behavior (Stein et al. 2009). This cohesion of sensory modalities is what gives rise to meaningful perceptual experiences. The interaction of the primary cortices is well established in the field of neuroscience by observing the superior colliculus at its neuronal responses (Stein 2012). The three principles of multisensory processing are: the principle of inverse effectiveness, which states that the multisensory integration is stronger in stimuli that are usually less effective in driving neuronal responses independently; the temporal principle, which states that the multisensory integration of separate modalities is stronger if the signals from these arrive at the same time; lastly, the spatial principle, which states that the multisensory integration is stronger if the stimuli from various modalities arises from approximately the same location (Stein 2012).

The multisensory integration theories have not always been at the forefront of perception studies, as the unimodal approach for understanding the senses and perception have dominated the literature. The feasibility of neural mapping of the brain has ignited a renewed interest in the perceptual mechanisms of the brain, allowing scientists to question the reductionist approach to understanding perceptual experience in isolated instances, and rather embracing a gestalt approach towards defining these mechanisms. Gestalt is a school of psychology that originated in Austria and Germany and was established in the 20th century, and from this movement derived a new foundation for the contemporary study of perception (Britannica 2017). The word “gestalt” derives from the German language and it means placed or put together; it is often translated to mean “form”, while in psychology the term refers to a “pattern” or “configuration” (Britannica 2017). This movement was founded with the purpose of adding a humanistic dimension to the sterile approach to the study of mental processes (Britannica 2017). This school of thought defined two fundamental principles; the first one was the principle of totality, which stated that conscious experience should be regarded holistically as a totality of the dynamic interactions within the brain; the second was the psychophysical isomorphism principle, which states that perceptual phenomena correspond with activity in the brain (DM 2017).

In accordance with the gestalt psychology movement, Gonzalo Justo also defined psychophysical isomorphism as a principle of perception, deriving from his research on brain dynamics in 1947. During his investigations, he realized that there was an inverted perception related to both vision and somatoception which extended to all the sensory systems with a spatial character (Fonrodona et. Al 2015). In his studies on the mechanisms and structures of spatial direction, Justo concluded that there is a cerebral recruitment representing a "spiral trajectory" that seeks a successive balance between the projection area of the brain and central action, meaning that in the perception of magnitude and direction there is a "sensory-cerebral correspondence", also defining this phenomenon as psychophysical isomorphism (Fonrodona et. Al 2015).

2.3 Visuospatial Perception

The perception of space is a visuospatial skill that includes navigation, depth, distance, mental imagery, and construction. These functions occur in the parietal cortex at the highest level of visual cognitive processes (Brain Center 2008). This multimodal ability helps us to process, identify, and imagine visual information from spatial relationships between objects in space. The visuospatial constructs are preconscious, and play an important role in guiding the visual flows of locomotion and actions such as pointing (Mountcastle, Steinmetz 1990.) It is involved in our ability to accurately reach for objects in our visual field. This skill underlies our ability to move around in an environment and orient ourselves appropriately. It is so vital to our survival that basic functions such as eating or walking would not be possible.

Spatial cognition is considered a supramodal function constructed from of converging inputs to the posterior parietal cortex from all sensory modalities, with a significant contribution from vision (Ungerleider & Mishkin 1982). The parietal lobe integrates information from multiple sensory receptors enabling complex tasks such as the manipulation of objects (Blakemore and Frith 2005). The somatosensory cortex and the visual cortex's dorsal stream are both parts of the parietal lobe. The ''where'' of visuospatial processing occurs in the dorsal stream, and the ''how'' is referred to as the ventral stream, such as the vision for action or imagination (Goodale and Milner 1992; Mishkin 1982). The parietal-occipital region is between the parietal, temporal, and occipital fields creating the junction of tactile-kinesthetic, auditory-vestibular and visual cortical centers. The principal function of these fields is to provide orientation within extrapersonal and intrapersonal space (Glezerman et al. 2002). These areas are also known as the extended Wernicke's area which is known for language associations (Ardila et al. 2016).

2.3.1 Photon-less Vision and Blind Imagination

"We see with the brain, not the eyes" -Bach-y-Rita, 1972

Studying the strategies and abilities of the sensory impaired, particularly blind subjects, is the most informative method by which to understand the mechanisms underlying perception. Many studies have concluded that the visual cortex is activated at a higher in blind individuals when performing tactile-spatial tasks such as braille reading or auditory processing, than in visually abled individuals (Sadato et al. 1996, Merabet 2016). In his study, Sadato (1996) used positron emission tomography (PET) scanning to measure activity in the visual cortex of his participants, both, blind braille readers and visually abled, while they engaged in somatoceptory discrimination tasks. His findings suggested that both the primary and secondary visual cortices were activated in blind participants during the discriminatory task, while the visually abled subjects showed no activation in the region, and both groups showed no activation where there was a tactile stimulus that required no discrimination (Sadato et al. 1996).

Visuospatial perception and visuospatial imagery are two different skills; however, they share some of the same driving neurological and psychological mechanisms. Mental imagery forms from multimodal sensory memories that relate to a particular object or event. This process of imagination is not exclusive to the visually abled, instead blind subjects employ alternative strategies for recalling or manipulating information. Albeit, the role that visual experiences play in mental imagination has not been definitive. Researchers have differing opinions about the extent at which visual perception informs imagery. Some argue that phenomenological visual experience is imperative for operations involving imagery, while others suggest that blind individuals are as effective, or more, in operating imagery (Szubielska 2014). The basis of this contradiction may be differing methodologies and conceptions on the process of mental imagery. For example, imagine an apple; it has multiple informational properties that characterize its color, shape, weight, smell, texture, etc. The multimodal experience of this object apple can be imagined as chemical, tactile, or visual image. When a task requires amodal spatial images from any of the sensory modalities, blind individuals perform as successfully as sighted subjects (Szubielska 2014).

The spatial reference framework from which we derive information about the environment can be conceived of by either an egocentric or an allocentric model. The allocentric representation considers information from an object-to-object reference framework, for example imagining or measuring distances by calculating the difference between objects. While an egocentric model is concerned with a self-to-object reference model, where the body at the center of experience gathers information from its movements and signals. Some studies have found that some congenitally blind individuals may have increased difficulty in allocentric spatial representation (Pasqualotto et al. 2012). Paqualotto et al. (2013) suggested that visual experience may be necessary in order to develop a preference for an allocentric framework. In his study, he found that blindfolded and late blind individuals prefer an allocentric reference frame, while congenitally blind participants prefer an egocentric reference frame (Pasqualotto et al. 2013). This preference for egocentric representation in blind individuals is also apparent while building spatial models from verbal descriptions of routes, unlike sighted individuals who were more efficient at forming these spatial constructs from survey descriptions (Noordzij et al. 2006).

In the case of blindness, the lack of visual input enables for new neural structures to emerge, organizing its perceptual system to prioritize non-visual modalities. What if someone’s visual perception was intact but the visual imagery was gone? They suddenly suffered a case of blind imagination. It was the case of MX, a man who lost his ability to see his internal visual imagery while retaining intact performance in visuo-spatial tasks, and the subject of the study conducted by Zeman AZ, Sala SD, Torrens LA, et al (2010). Their findings suggested that MX adopted new cognitive strategies in order to perform the imagery task. While performing a mental rotation task MX managed a normal accuracy range by using a perceptual mapping strategy. He also managed normal accuracy when attempting tasks of visual imagery by verbally encoding them (Zeman et al. 2010). There have been other cases of blind imagination, usually in individuals that have sustained a head injury. In Sir Brain's (1954) research studies he found that some subjects were still able to draw maps of their houses and their route from home to work; however, they reported great difficulty as they had to reimagine spatial cues without visual imagery as they were formally accustomed. One of his subjects reported "When I dream, I seem to know what is happening, but I don't seem to see a picture. I can dream about a person without seeing them, and I can remember the person, but not having seen them." (Brain 1954). These examples suggest that there is a disassociation with the phenomenal experience of visual imagery and the performance visual imagery tasks.

2.3.1 Seeing Space with Sound

Audition also informs visuospatial processes by the sound's sensed time of arrival, which is processed by the parietal cortex. Manipulating the speed at which audio reaches each ear can result in realistic effects artificially generated. The 3D3A Lab at Princeton University (2010), led by Professor Edgar, studies the fundamental aspects of spatial hearing in humans. They have developed a technique for sound playback that results in the realistic rendering of three-dimensional output, making it possible to simulate the sound of a flying insect circling one's head with laptop speakers and without headphones. Their research hones on the few cues by which humans perceive the provenience of sound. One signal being the difference between the two intervals of time that happens when audio reaches one ear before the other. The second cue is the amplitude or volume differential of the sound arriving at the two ears (Wood 2010).

Human echolocation uses the same principles of 3D-audio recreations, accounting for time intervals and volume differentials. Echolocation is a means for navigation, object location, and even material differentiation. Mammals such as bats and dolphins have highly sophisticated hearing systems that allow them to differentiate the shape, size, and material of their targets. Their auditory systems are specialized based on their different target needs. Dolphins tend to use broadband, short-duration, narrow beams that are tolerant to the Doppler effect, while bats use more extended echolocation signals that seek the detection of the Doppler shift (Whitlow 1997). In humans, echolocation is a learned process, and while some humans depend on this skill for navigation, target location, and material differentiation. There are no organs in the human auditory system specialized for echolocation. Instead, our brain is adaptable, and sensory substitution can achieve this technique.

The World Access for the Blind is an organization that helps individuals echolocate; their motto being ''Our Vision is Sound'' (2010). Daniel Kish is a blind, self-taught echolocation expert who has been performing this skill, since he was a year old. He is the president of this organization and describes himself as the ''Real Batman'' (Kish 2011).

Kish is a master of echolocation; he interprets the return of his mouth clicks gaining a rich understanding of his spatial surroundings. His and some other congenitally blind individuals' early adoption of echolocation techniques seems to develop naturally. Some studies show that blind individuals demonstrate exceptional auditory spatial processing. These results suggest that sensory substitution is taking place, and the functions of the occipital lobe are appropriated for audio processing stemming from their deprived visual inputs (Collignon et al. 2008).

Kish's (2011) dissemination of his echolocation technique has helped hundreds of blind people to regain ''freedom,'' as he describes it. Those who have learned to exercise mouth-clicking echolocation can navigate space, ride bikes, skateboards, and ice skate. They may also gain the ability to locate buildings hundreds of yards away with a single loud clap. Their clicking is a language that asks the environment — ''Where are you?'' with mouth sounds, cane tapping, and card clips on bicycle wheels (2010). These clicks return imprints of their physical encounters with their environment as if taking a sonic mold of space.

The skill of echolocation is a learned behavior that sometimes occurs naturally in congenitally blind individuals. It seems to be a survival mechanism by sensory substitution, where areas of the brain re-wire processing power from one absent signal to another. Some blind individuals have learned to process the auditory feedback as a sonic mold of their environment by instruction, for example, the pupils of Daniel Kish. Since human echolocation skills do not always develop naturally, it is possible that sighted individuals can also achieve this ability while presented with the ideal circumstances. In this case, sighted individuals should, maybe, restrict their vision to allow for the auditory feedback to be processed by the occipital lobe, similar to the perceptual conditions of a blind individual.

3. Assistive Device Art

This chapter brings forward the concept of Assistive Device Art (ADA) as a way of defining the phenomena that surround prosthetic related artworks where Assistive Technology (AT) becomes a product of desire by abled bodies. Assistive Technology is a gateway to human enhancement, inspiring the limits of extra-sensory computing interfaces that together with Art, as a means of aesthetic and experiential study, result in ADA tools. These interfaces inquire about the plasticity of our physiology, they facilitate alternative sensory viewpoints, opening empathic channels by activating curiosity. They seek to enhance perspectives, to display new ways of seeing and sensing our environment, our cities, our landscapes. ADA goes beyond replacing or restoring function; these tools are not seamless utilitarian AT, they are playfully designed to reveal the multimodal precepts that inform our sensory awareness. They give participants new abilities by refocusing their attention to alternative senses, from which they rediscover their surroundings lending them to reflect upon what constitutes skill. ADA tools borrow from a mixed methodology that includes psychophysical and user experience evaluations, rapid prototyping design and development within an artistic context. These artworks reimagine technological displays through the lens of unique physiological architectures that inspire the smell of time, the sound of space. The foundation of these ADA interfaces and functionalities comes from an interactively assistive solution.

This thesis brings forward the concept of Assistive Device Art (ADA) as coined by the author. It is a definition for the emerging cultural phenomena that integrates Assistive Technology and Art. These works of art involve the mediation of sensorimotor functions and perception, as they relate to psychophysical methods and conceptual mechanics of sensory embodiment. Psychophysics is the methodological quantification of sensory awareness in the sciences, while the theoretical aspects of embodiment have a more exploratory nature—they seek to investigate perception open-ended. The philosophical view of embodied cognition depends on having sensorimotor capacities embedded in a biological, psychological, and cultural context (Rosch et al. 1991). The importance of this concept is that it defines all experience as not merely an informational exchange between environment and the mind, but rather an interactive transformation. This interaction of the sensorimotor functions of an organism and its environment are what mutually create an experience (Thompson 2010).

3.1 Perception Spectacles

Assistive Device Art sits between this transformational crossroads of sensory reactions in the form of tools for rediscovering the environment and mediating the plasticity of human experience. This art form interfaces electromechanically and biologically with a participant. It is functional and assistive, and its purpose is, furthermore, a means for engaging the plasticity of their perceptual constructs. Assistive Technology (AT) is an umbrella term that encompasses rehabilitation and prosthetic devices, such as systems which replace or support missing or impaired body parts. This terminology implies the demand for a shared experience, as the scope of restoration drives it to normalcy, rather than the pure pursuit of sensorimotor expansion. Regardless of its medium, technology is inherently assistive. However, AT refers explicitly to systems designed for aiding disabilities. Organisms and their biological mechanisms are a product of the world in which they live. All bodies have evolved as extensions of the sensory interactions with our environment. In our quest as human organisms, the need to reach, manipulate, feel, and hold manifested as a hand. Hutto (2013) defines the hand as ‘‘an organ of cognition’’ and not as subordinate to the central nervous system. It acts as the brain’s counterpart in a ‘‘bi-directional interplay between manual and brain activity’’.

The prosthesis is an answer to conserve the universal standard of the human body, as well as the impulse to extend beyond our sensorimotor capacities. The device as separate or as a part of us is mechanized as an extension of our procedural tool which is the agency that activates the boundaries of our experience. This intentionality trans- posed through a machine or device belongs to the body with a semi-transparent relation. In this context, transparency is the ease of bodily incorporation, the adoption of a tool that through interaction becomes a seamless part of the user. Ihde (1979) conceptualizes the meaning of transparency as it relates to the quality of fusion between a human and machine. Interface transparency is the level of integration between the agent’s sensorimotor cortex and its tool.

ADA tools serve the participant as introspective portals to reflect on this process of incorporation. These cognitive prosthetic devices become ever more incorporated with practice, more transparent, enhancing our ability to re-wire our perception. The transformation of our awareness does not only happen by an additive and reductive process of incorporation, but also by the accumulative experience gained through the shift these devices/filters pose on the participant's reality. Assistive Device artworks are performances that reveal the plasticity of the mind, while it is actively incorporating, replacing, and enhancing sensorimotor functions. These performances are interactive and experiential, aided by an interface worn between the sensory datum and the architecture of our physiology. Art is about communication and the perception of ideas. These performances transpose specific sensations to convey designed experiential models. As the participant performs for themselves by engaging these tools, they explore a new construct of their mediated environment and the blurring of incorporation between body agency and instrument. ADA centralizes and empowers the urge to transcend bodily limitations—both from necessity as Assistive Technology and as a means to playfully engage perceptual expansion. The desire to escape the body is what activates our state as evolving beings impelled by the intentionality of our experience.

3.2 Device Art: Playful Understanding of the Mind

The term ''Device Art'' is a concept within Media Art which encapsulates art, science, and technology with interaction as a medium for playful exploration. Originating in Japan in 2004 with the purpose of founding a new movement for expressive science and technology, it created a framework for producing, exhibiting, distributing, and theorizing this new type of media art (Iwata 2004). This model takes into consideration the digital age reproduction methods which make possible the commercial attainability of artworks to a broader audience. As a result, this movement expanded the art experience from galleries and museums and returned to the traditional Japanese view of art as being part of everyday life (Kusahara 2010). This consumable art framework is common in Japanese art, as it frequently exists between the lines of function, entertainment, and product.

This art movement is part of the encompassing phenomenon of Interactive Art, which is concerned with many of the same guidelines of Device Art, but envelopes a greater scope of work. Interaction in art involves participants rather than passive spectators, where their participation completes the work itself. The concept of activation of artworks by an audience has been part of the discussion of art movements since the Futurists' Participatory Theater and further explored by others, such as Dada and the Fluxus Happenings. These artists were concerned with bringing the artworks closer to ''life'' (Dinkla 1996). Interactive Art usually takes the form of an immersive environment, mainly installations, where the audience activates the work by becoming part of it. The ubiquitous nature of computing media boosted this movement, making Interactive Art almost synonymous with its contemporary technology.

Device Art albeit interactive, technologically driven, and with the aim of bringing art back to daily life, has some crucial differences from Interactive Art. Device Art challenges the value model that surrounds the art market by embracing a commercial mass production approach to the value of art. Artworks of this form embody utility by its encapsulation as a device, which is more closely related to a product. The device is mobile or detachable from a specific space or participant; it only requires interaction. Device Art frees itself from the need of an exhibition space; it is available to the public with the intent of providing playful entertainment (Kusahara 2010).

3.3 Cultural Aesthetics: Products of Desire

Assistive Device Art stems from the merging of AT and Device Art, and it is a form of understanding and expanding human abilities. This concept is closely related to the concurrent movements of Cyborg Art and Body Hacking, which include medical and ancient traditions of body modification for aesthetic, interactive, and assistive purposes. They explore the incorporation of contemporary technology such as the implantation of antennas and sensor–transducer devices. For instance, in 2013, Anthony Antonellis performed the artwork Net Art Implant, where he implanted an RFID chip on his left hand. This chip loads re-writable Web media content once scanned by a cell phone, typically a 10-frame-favicon animation (Antonellis 2013). Cybernetics pioneer Dr. Kevin Warwick (2002) conducted neuro-surgical experiments where he implanted the UtahArray/BrainGate into the median muscles of his arm, linking his nervous system directly to a computer with the purpose of advancing Assistive Technology. Works within the Cyborg and Body Hacking movements often include, if not almost require, the perforation or modification of the body to incorporate technology within it.

Assistive Device Art is non-invasive or semi-invasive. It becomes incorporated into our physiology while remaining a separate, yet adopted interactive device. The appeal behind these wearable prosthetic artworks is that users are not compromising or permanently modifying their body; instead, they are temporarily augmenting their experience. Cyborgs, people who use ADA, and those who practice meditation are all engaging neuroplasticity. These engagements fall under various levels of bodily embeddedness, but they all show a willingness to interface with their environments in a new type of transactional event.

The prosthesis is becoming an object of desire, propelled by the appeal of human enhancement. While not only providing a degree of ‘‘normalcy’’ to a disabled participant, it also enables a kind of superhuman ability. Pullin (2009) describes eyeglasses as a type of AT that has become a fashion accessory in his book, ‘‘Design Meets Disability’’. Glasses are an example of AT that have pierced through the veil of disability by becoming a decorative statement and an object prone to irrationally positive attribution. Somehow, what seems to be a sign of mild visual impairment is a symbol of sophistication. ADA strives to empower people by popularizing concepts of AT and making them desirable. Art is a powerful tool for molding attitudes and proliferating channels of visibility by communicating aesthetic style and behavior. Through the means of playful interaction, phenomenological psychophysics, biomedical robotics, and sensory substitution, ADA is made to appeal aesthetically, become desirable, and useful inclusively to everyone.

3.3 Assistive Device Artworks: The Prosthetic Phenomena

Auger and Loizeau (2002) designed an *Audio Tooth Implant* artwork which consists of a prototype and a conceptual functional model. Their prototype is a transparent resin tooth with a microchip cast within it, floating in the middle. Conceptually, this device has a bluetooth connection that syncs with personal phones and other peripheral devices. It uses a vibrating motor to transduce audio signals directly to the jawbone providing bone conduction hearing. This implant was created with the premise to be used voluntarily to augment natural human faculties. The intended purpose of this artwork was a way to engage the public in a dialog about in-body technology and its impact on society (Schwartzman 2011). This implant device does not function, but it is skillfully executed as a ‘‘look and feel’’ prototype. Because of the artists’ careful product design consideration and their intriguing concept which lied on the fringes of possible technology, this artwork became a viral internet product. Time Magazine selected this artwork as part of their 2002 ‘‘Best Inventions’’ (Schwartzman 2011). In the public eye, this artwork became regarded as a hoax, as the media framed it out of context from its conceptual provenience, and confused it with a consumer product. However, this meant that their work fulfilled its purpose as a catalyst for public dialog about in-body technology, and more importantly, it expressed its eager acceptance.

Another work that resonates with this productized aesthetic is Beta Tank’s *Eye-Candy-Can* (2007). Through their art, they were searching for consumer attention, a way of validating the desire for sensory-mixing curiosity. This artwork is also a ‘‘look-and-feel’’ prototype that blurred the lines of product, artwork, and assistive technology. They drew inspiration from Paul Bach-Y-Rita’s previously mentioned Brain Port, the AT device that could substitute a blind person’s sight through the tactile stimulation of the tongue. This device includes a pair of glasses equipped with a camera connected to a tongue display unit. This tongue display unit consists of a stamp-sized array of electrodes, a matrix of electric pixels, sitting on the user’s tongue. This display reproduces the camera’s image by transposing the picture’s light and dark information to high or low electric currents (Bach-Y-Rita 1998). Beta Tank used this idea and fabricated a ‘‘look-and-feel’’ prototype, which consisted of a lollipop fashioned with some seeming electrodes and a USB attachment as its handle. They also created a company that would supposedly bring this technology to the general consumer market as an entertainment device that delivered visuo-electric flavors (Beta Tank 2007). However, these electrode pops where once again not functional, but, instead, they conceptually framed the use of AT as a new form of entertainment. In contrast, the *GoFlow* device, previously mentioned in the introduction, is an ADA example of completely functional commodified AT (2012). Once an open-source DIY device promising intellectual enhancement, the *GoFlow* project is now a company called foc.us delivering consumer grade devices (fo.cus 2017). From hacking project to consumer electronics manufacturing, this novel idea to productize AT lab technology is an exemplary case to the framework of ADA.

Not all artworks that could be considered ADA have to be desirable products for a consumer market. Most of these artworks are capable of becoming real products, but their primary objective is to provide an experience. They serve as a platform to expand our sensorimotor capacities as a form of feeling and understanding our transcendental embodiment. One of the earliest artworks that could be an example of AT is Sterlac's (1980) *Third Arm*, a robotic third limb attached to his right arm. It has actuators and sensors that incorporate the prosthesis into his bodily awareness and agency (Sterlac 1980). This prosthetic artwork does not restore human ability; instead, it expands on the participant's sensorimotor functions transferring superhuman skills by allowing them to gain control of a third arm. This artwork questions the boundaries of human–computer integration, appropriating Assistive Technology for art as a means of expression beyond medical or bodily restoration. This work is not concerned with the optimal and efficient function of a third hand; it physically expresses the question of this concept's utility and fulfilling its fantasy. Professor Iwata's (2000) *Floating Eye* is another work that expresses this transcendence of embodiment. This artwork includes a pair of wearable goggles that display the real-time, wide-angle image received from a floating blimp tethered above the participant (Iwata 2000). This device substitutes the wearer's perception from their usual scope to a broader, outer-body visual perspective, where the participant can perceive their entire body as part of their newly acquired visual angle. This experience has no specific assistive capabilities regarding restoring human functions, but it widens the perspective of the participant beyond their body's architecture. It becomes a perceptual prosthesis that extends human awareness.

Some psychophysical experimental devices that are not art have the potential to be considered ADA. Take, for example, the work of Lundborg and his group (1999), ''Hearing as Substitution for Sensation: A New Principle for Artificial Sensibility,'' where they investigate how sonic perception can inform the somatosensory cortex about a physical object based on the acoustic deflection of a surface. Their system consists of contact microphones applied to the fingers which provide audible cues translating tactile to acoustic information by sensory substitution (Lundborg et al. 1999). While the presentation of this work is not in the context of art, its idea of playing with our sensory awareness resonates with the essence of ADA's purpose of exploratory cross-modal introspection.

4. Methodology: Designing an Assistive Device Art Tool

The Sensory Pathways for the Plastic Mind is a series of ADA that explores consumer product aesthetics as well as delivering new sensory experiences (Chacin 2013). These wearable extensions aim to activate alternative perceptual pathways as they mimic, borrow from, and may be useful as Assistive Technology. This series extends AT to the masses as a means to expand perceptual awareness and the malleability of our perceptual architecture. They are created by appropriating the functionality of everyday devices and re-inventing their interface to be experienced by cross-modal methods. This series includes the two case studies in this research, *Echolocation Headphones* and *IrukaTact Glove,* as well as works not included such as *ScentRhythm* and the *Play-A-Grill*. The *ScentRhythm* is a watch that uses olfactory mapping to the body's circadian cycle. This device provides synthetic chemical signals that may induce time-related sensations, such as small doses of caffeine, paired with the scent of coffee to awaken the user. This work is a fully functional integrated prototype. Play-A-Grill is an MP3 player that plays music through the wearer's teeth using bone conduction, similar to the way cochlear implants transduce sound bypassing the eardrum (Chacin 2013). Play-A-Grill is not just a ''look and feel'' prototype; its functionality has been implemented and tested, unlike Auger and Loizeau's Audio Tooth Implant. This series exhibits functional AT that is desirable to the public. The combination of product design aesthetics and the promise of a novel cognitive experience has made some of the works in this series which become part of the viral Internet media. In this way, they have also become validated as a product of consumer desire.

4.1 Interdisciplinary Approaches to Tool Design

Assistive Device artworks are created with an interdisciplinary approach that considers functionality with practical applications, as well as fulfilling an aesthetic, experiential, and awareness driven purpose. While these strategies are not mutually exclusive, there is a delicate balance for achieving a satisfactory evaluation method, where one approach is not more important than the other. For instance, in the design and concept formulation of the *Echolocation Headphones*, the technical functionality of this device is crucial to achieving its purpose as a perceptual introspection tool. In this specific case, the *Echolocation Headphones* first need to aid in human echolocation to provide the experiential awareness of spatial perception. And in the case of *IrukaTact* the first identifiable need is to provide an effective way for displaying haptic information underwater. As for the echo locative applications of both interfaces, they must be designed to display a signal with congruent directionality. This means that the artificial echo-signal must originate from an egocentric location, the participant's original modalities for which they usually intake spatial information. This visuospatial ADA tools must be able to enhance the perception of space through other modalities, training participants to gain a new relationship to their surroundings. While AT is designed to specifically aid and, perhaps, restore functions, an Assistive Device artwork is concerned with the playful means by which an experience forms perceptual awareness. Assistive Technology aims to develop more efficient systems by evaluating and comparing devices to previously existing products, whereas Assistive Device artworks are less concerned with seamless utility or ability restoration. Instead, these artworks are for a diverse participant base, designed with an experiential basis by which all participants can expand their perception regardless of their need for echolocation as a means of daily navigation.

The interaction design for ADA pieces have a foundational basis in appropriating the wearable functions, uses, and interactions of common wearable devices, such as goggles, watches, spoons, and mouthpieces. They are often reconstructions of these devices with an exchange in sensory functionality. Their interaction has been reinvented not solely for accessibility purposes, rather as an experiential artwork. ADA applies AT methods such as cross-modal psychology applications to common devices that in their form and utility allow participants to question how we learn, and how do our brains adapt to new channels of perception. ADA development is to create a device and performance composition for the translation, adaptation, and learning of new sensory processes. This framework sits within the fields of cross-modal psychology, assistive technology, and interaction design. Many of the applications for sensory substitution experiments emerge for accessibility needs, which is the quest for making technologies and information available to anyone. ADA is a type of testing hardware that provides a fresh outlook for new human-computer interfaces that centers on sensory translation and adaptation. Though not all of ADA tools prove to be entirely efficient, AT efficiency is not the main goal of the interfaces. The goal is to create interfaces that expand experiential awareness and to provide an insight on the limits at which normally abled participants are willing to engage with perceptually-shifting technology.

In the world of consumer electronics, there are well-defined aesthetics that drive product appeal. ADA often uses the aesthetics of product design resonating with consumer culture similar to Speculative Design. Dunne and Raby (2014) brought forward this concept of Speculative Design a means of exploring and questioning ideas, speculating, rather than solving problems through the design of everyday things, a way to imagine possible futures. The critical aspect of this concept lies in the imagination and possibility that a model represents, rather than its actual technical implementation. Houde and Hill (1997) defined a method for prototyping where each prototype would be designed to fulfill three categories for full integration: ‘‘look-and-feel,’’ ‘‘role,’’ and ‘‘implementation’’. In their design process, each prototype would lie somewhere between these three categories and slowly become integrated as each new iteration borrowed from the previous one. The ‘‘look-and-feel’’ prototype actualizes an idea by only concerning the sensory experience of using an artifact (Houde and Hill 1997). This type of prototype has no technical implementation, it just looks and feels like a real product. This type of prototype is closely related to ‘‘vaporware,’’ which is the term used in the product design industry referring to a product that is merely representational. It is announced to the public as a product, but not available for purchase. Similarly, in vaporware, the aesthetic design and role are fully implemented, but also void of technical functionality. Finished products of Speculative Design, vaporware, and ‘‘look-and-feel’’ prototypes rely on aesthetics to express an idea. This approach to design resonates with the traditional view of the object in art, where it is devoid of practical function. Its utility has been stripped, and its form reincorporated as part of a concept in the context of art. ADA takes into account the same aesthetic design principles that surround these products of design. However, depending on their purpose, most of these ADA artworks are often entirely integrated prototypes, including their wholly functional technical implementation. Works in this realm are concerned with the experience of incorporation, rather than merely hinting at the idea.

4.2 Public Presentation and Dissemination

Prototype, artwork, vaporware, venture capital product, and off-the-shelf are ambiguous terms in the cross-fire of defining an idea when it becomes public through the media. Consumers and journalists identify and publicize these artworks as real products on their own, driven by their desire for new technological advancements. Albeit, often Assistive Device artworks are intendedly designed to become viral internet products with the purpose of provoking public reactions that measure the consumer desire for body extensions and technological upgrades to our bodies. This ‘‘viralization’’ validates what these artworks represent—the human transcendental desire to augment and enhance their embodiment. The popularization of wearable technology through the Internet has become a method for artistic exhibition and public dialogue outreach. While art often seems stagnant in art galleries, the boards of social media are open channels for discussion. The click-economy has opened the doors to a new way for electronic media artists to engage the public. Prototypes that never made it to production stage were dusty models in the corner of a lab, now they have access to the same center stage as the big-player consumer market. While they may not at all profit from sales, as often times ADA is a single original prototype, they profit from publicity. This outreach method by which to test consumer interest gauges the pulse for novel interactions. The dialogue created via an internet “product” is recorded and retrievable. This way of presenting ADA keeps a public account of the dialogue that these ideas generate.

Beyond the scope of digital outreach, conference demonstrations and art exhibition are two different models for engaging public participants in a physical environment to tests ADAs beyond lab experimentation. Taking prototypes out of the clinical environment of research facilities allows for a critical assessment of the work in a real-world environment with a wider-rage public. While the prototypes may suffer from technical instability, as they are often delicate original mechanisms, public presentation is a test of resilience physically, experientially, and conceptually. It is also a test of aesthetic appeal; even if an ADA prototype is being presented in an academic conference demonstration and not an art gallery or exhibition, its aesthetic appeal would change the reception of the device. Design considerations will define the opportunity to engage more public attention, and thus receive more critical feedback for improvement. ADAs should strive for flexibility, creating interfaces that are inquisitive in a metaphorical and conceptual basis, while simultaneously demonstrate new applications in both design and technical implementations.

4.3 Open-Access Engineering

ADAs should strive to be open-source tools made by borrowing and contributing to scientific research while exploring the artistic capabilities of interfacing the body via atypical venues of physiology. These alternative displays are often created using open-hardware modules and hacking techniques. Making technology that helps people with limited senses is a small industry of privatized technology therefore attaining these devices is difficult and expensive. Open-hardware can facilitate making these technologies available to people that need them the most, for as affordable as cost of their materials. Also, sharing methods and techniques in this area of HCI development provokes more thinkers and tinkerers of open-source hardware to contribute to existing or create new interfaces for information display.

The availability of accessible hardware toolkits that promote open-source engineering has revolutionized device design. Platforms such as YouTube, Arduino, and Processing offer free and open access to electronics prototyping methods appealing to non-engineers and causing new methods and motives for tool design. Electrical and computer science reverse-engineers are emerging from creative fields, interaction design among other artistic practices. Their inventive approach is more concerned with the humanistic aspects of tool design. They are focused on concept, meaning, public reception, and igniting dialogue. This strategy is concerned with the relational matters of the tool to the user, society, and its cultural underpinnings. These developers take a top-down approach, beginning with an idea and gaining insight by deconstructing its components into sub-systems as a way of reverse engineering. This technique poses more complex challenges at the beginning of the process, as the ideation phase will examine global questions, and in a way, create a new problem to be solved. The top-down approach is iterative, it generates numerous prototypes using qualitative and instinctual strategies, focusing on the essential aspects of an idea, and addressing the necessary technical challenges as arise. Typically, computer scientists and electrical engineers are trained to develop interfaces using a bottom-up approach. They have a strong foundation of scientific principles and highly data-driven testing methods, where the quantifiable aspects of interface inception, production, testing, and deployment are the most important. This approach is flexible at the beginning of the process, starting with smaller parts of a system and building sub-sections to be joined and complete a model. A bottom-up approach may be more appealing to engineers who are interested in solving problems, rather than planning on new problems to solve.

Both approaches to tool design have their particular benefits; top-down can provide preliminary observations on usability and gauge the interest of a novel interaction, while bottom-up yields stable, dependable, and efficient devices. ADA tools can be most effective when designed with a top-down approach as there is now copious amounts of information accessible detailing methods and techniques for implementing microprocessor driven devices prototypes. The focus of development for ADA tool lies on questioning how to expand sensory awareness which are concepts difficult to test with a bottom-up approach. The holistic view of multimodal perception encourages interface design to consider a unified vision that firstly proposes a new mode for information reception or sensorimotor adaptation.

4.4 Designing for Sensory Plasticity

We can arrive at the same understanding of an experience based on a few signals. Depending on the different goals of perception, various inputs can collect useful information, for example: to learn about our spatial surroundings one can use proprioception, audition, sight, and kinesthetic senses. Taste, is not a very efficient way of learning about our spatial surroundings. Understanding the senses and how they are interpreted in the mind is crucial for defining the new models of interaction and provoke meaningful inquiry on ADA perceptual expansion devices. The human senses are divided into three main categories: mechanoreceptors (audition and somatoception), chemoreceptors (olfaction and gustation), and photoreceptors (vision). Most of the senses fall under the mechanoreceptor category, more specifically under the somatic sense, from which we feel thermoception (temperature), nociception (pain receptors), and proprioception. This also includes the vestibular sense, which is our sense of balance located in our inner ear, one of the most finely tuned mechanoreceptor systems of the body. The perception of the world around us is a delicate and balanced dance between our sensory and motor cortex. One interprets information, and the other one mandates new functions allowing the flux of our perception.

As established in the introduction, neuroscientists have begun to understand the brain as a plastic organ that allows for reorientation and re-establishment of processes. Marina Bedny, an MIT postdoctoral associate in the Department of Brain and Cognitive Sciences says- “Your brain is not a prepackaged kind of thing. It doesn’t develop along a fixed trajectory, rather, it’s a self-building toolkit. The building process is profoundly influenced by the experiences you have during your development.” (2011). Our brain is so elastic, we can add other senses to it. For example, surgically implanting magnets into the fingertips has become a new body modification trend because with these implants one can sense the intensity and shape of magnetic fields in close proximity. The brain cannot be compartmentalized, since there is not a specific part of the brain dedicated to process magnetic information. Our brains are capable to interpret new sets of available information from any kind of phenomenological stimulus given the right tools. It’s possible to plug and play with your sensory field and achieve alternative pathways of perception. Participants engaged in sensory substitution or augmentative devices while re-channeling or extending their senses, achieve a level of brain plasticity and machine-bio-cooperation. ADA interfaces aim to open new modes of perception for all users, striving to understand sentient physiological and psychological phenomena that expand the perceptual potential of new interfaces for computing media.

Interfacing the body is the most delicate aspect of this study because it intimately examines cultural and biological implications of physiology. Taking safety precautions is imperative, as this research is borrowing from a multitude of conceptual perspectives and scientific methods, incorporating precautions during experimental design is the only way to engage in productive creative inquiry. Taking a playful view on performance allows for a certain malleability between willingness to participate and curiosity. This egocentric approach to the experiential art engages viewer at a very personal physiological level, that beyond vulnerability it simultaneously provokes an urge of curiosity to experience something new. These devices are conceptualized or developed in accordance with perception and sensory substitution principles. Albeit, not all ADA has complete functionality sometimes existing only as vaporware, the implementation of technical aspects of experiential design give more insight about the quality of an experience. Data oriented research gives an insight about the perceptual performance of participants while wearing an ADA interface. When the functionality of the device is fully or at least partially implemented more information can be gathered through psychophysical experimentation. There are well-established methods in this area in order to find how stimulus may be perceived by a human user. These types of experiments usually include perceptual accuracy of the participant while a stimulus is being transduced, just noticeable difference (JND), absolute threshold, among others. A common example of an absolute threshold psychophysical experiment is the typical hearing test. In this experiment, a participant is presented with selected frequency tones within the audible spectrum in an increasing or decreasing order, while they are asked to discern each tone therefore arriving at their own particular range of audition.

The ADA is a model for experimentation with non-invasive devices that can supplement or substitute our general and current perceptual abilities. Many times, the functionality of these devices derives from existing scientific research on perception. It incorporates AT with a top-down approach that deconstructs the design common devices and appropriates some of their functions to be transduced to other sensory modalities. It explores how AT and consumer technology can merge and at which extent it can adopted by common users via its commodification. ADA inquiries about future cross-modal applications for wearable devices. In understanding the advantages and disadvantages of the normal brain and the disabled brain lie many unexplored traits that can be useful for survival. Designing devices that facilitate extraordinary ability or serve as training apparatuses for further engraving alternate paths for neuronal operations such as seeing with tactile information, is one path to discover what non-obvious evolutionary traits our species might benefit from.

4.4.1 Adopted Assistive Displays- Touch and Listen

Tactile displays are an example of accessible technology that has made a leap on to popular applications. Braille display devices and vibrotactile stimulation, also used in event simulations, has been used to aid blind people to interface with computational media. Now we see mobile devices becoming reactive to touch by using emitting a vibration through a motor, previously used solely for incoming calls in silent mode, as a display method to show the user that an icon has been selected. Soon we will begin to see haptic simulation effects in mobile consumer electronics that will create textures and different somatic stimuli with localized matrix generated vibrations, enhanced braille displays, rather than the single motor in current devices. It will be greater than the difference between black and white or color television; it will be perhaps the difference between TV and a flashlight.

Voice command and recognition is another emerging form of AT that is permeating popular applications. Previously, the main users of audio computer UIs such as screen readers were the visually impaired. Now, we can see regular people voice commanding their phones through a Bluetooth earpiece calling their virtual assistants, whether it is Siri for Apple Devices, Cortana from Windows or asking Alexa, the home voice command personal assistant from Amazon, to "Please, turn off their air-conditioning." What other perceptual methods are useful for interface design?

5. Implementation- Case Studies

This section describes the design process, psychophysical evaluation, and future applications of the two case studies; *Echolocation Headphones* and *IrukaTact Glove.* These case studies are examples of ADA tools created specifically to increase the plasticity of spatial perception. In both cases we inhibited the vision of both experiment participants and members of the public when engaging the translating interfaces, whether they were experiencing audible echolocation or in the case of the echo-haptic translation. This inhibition of the visual field is what allows for the sensory substitution process to begin to take place, allowing the ADA participants to embody a new sensory architecture by which to engage in alternative visuospatial imagery.

The *Echolocation Headphones* is an ADA tool that aids human echolocation, namely the location of objects and the navigation of space through audition. The interface is designed to substitute the participant's vision with the reception of a focused sound beam. This directional signal serves as a scanning probe that reflects the sonic signature of a target object. Humans are not capable of emitting a parametric echo, but this quality of sound gives the participant an auditory focus, similar to the focal point of vision. In the *Echolocation Headphones* case study, we define the design parameters and technical aspects of the tool and analyze the perceptual performance of participants while wearing this tool. This tool is designed to aid human echolocation, facilitates the experience of sonic vision, as a way of reflecting and learning about the construct of our spatial perception.

IrukaTact haptic module, a wearable device for underwater tactile stimulation of the fingertips. It utilizes an impeller pump that suctions surrounding water and propels it onto the volar pads of the finger, providing a hybrid feel of vibration and pressure stimulation. In this case study, we evaluate the performance of this tool by conducting a series of experiments, such as testing the displayed force and flow rate, and the participants' absolute threshold and perceptual resolution while wearing the device. *IrukaTact* has an echo-haptic utility when paired with a sonar sensor transposing distance data from an ultrasonic range-finder into haptic feedback, giving users a quasi-parallel sense of touch. The effectiveness of this translation has been tested in two ways; *DemoTank* units and an *IrukaTact* sonar directional torch for aqueous environments. This cross-modal transaction of visuospatial information has assistive capabilities for aquatic environments where human vision is mostly hindered or disabled by those conditions. This study concludes with the design of the *IrukaTact* glove as an Assistive Device Art tool.

Both, *Echolocation Headphones* and *IrukaTact Glove* are tools that emerge from assistive technology and go beyond restoring function as a way of expanding the sensory array of computational displays. This section expands on each case study while relating its provenience and performance to the ADA conceptual and psychophysical approach of tool design.

5.1 *Echolocation Headphones*: Seeing Space with Sound

Echolocation Headphones are a pair of opaque goggles which disable the participant's vision. This device emits a focused sound beam which activates the space with directional acoustic reflection, giving the user the ability to navigate and perceive space through audition. The directional properties of parametric sound provide the participant a focal echo, similar to the focal point of vision. This study analyzes the effectiveness of this wearable sensory extension for aiding auditory spatial location in three experiments; optimal sound type and distance for object location, perceptual resolution by just noticeable difference, and goal-directed spatial navigation for open pathway detection, all conducted at the Virtual Reality Lab of the University of Tsukuba, Japan. The Echolocation Head- phones have been designed for a diverse participant base.

They have both the potential to aid auditory spatial perception for the visually impaired and to train sighted individuals in gaining human echolocation abilities. Furthermore, this Assistive Device artwork instigates participants to contemplate on the plasticity of their sensorimotor architecture.

5.1.1 Device Design

The priority for this interface is to place the sense of hearing at the center of this tool design. The parametric speaker was attached to the single square lens of a pair of welding goggles. Because this device performs sensory substitution from vision to audition, appropriating the functional design of glasses is a natural choice that pre- vents sight and replaces it with a central audible signal. Furthermore, the signal for an echo usually originates from the frontal direction of navigation, such as from the mouth of a human echolocation expert. Welding goggles are designed to protect the wearer from the harsh light, which makes them attractive for acoustic spatial training necessary for sighted subjects. In informal settings, the goggles do not entirely deprive the sense of sight purposefully, so that sighted participants can get accustomed to spatial mapping from vision to audition. However, when used for experimental purposes, the protective glass is covered with black tape to cover the wearer's vision completely. Giving the participants the freedom to explore their surroundings is a crucial interaction for experiencing audio-based navigation and object location.

5.1.1.1 Mechanism: Technical Aspects

The main component of the *Echolocation Headphones* (Fig. 1) is a parametric speaker that uses a focused acoustic beam. The wavelength of an audible sound wave is omnidirectional and larger than an ultrasonic wave. The parametric sound is generated from ultrasonic carrier waves, which are shorter and of higher frequency, above 20 kHz. When two intermittent ultrasonic carrier waves collide in the air, they demodulate, resulting in a focused audible beam.

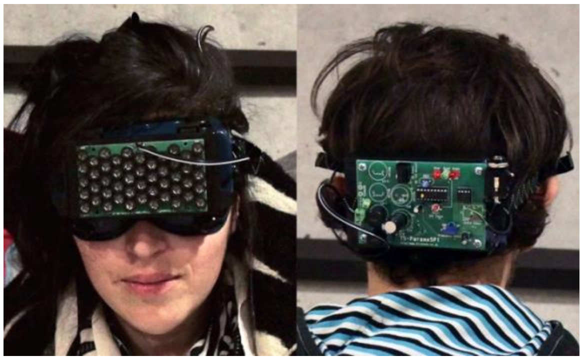


Figure 1: *Echolocation Headphones* front view (left) and back view (right).

This signal becomes perceivable in the audible spectrum while retaining the directional properties of ultrasonic sound. For example, one ultrasonic wave is 40 kHz; the other is 40 kHz (plus the added audible sound wave). As shown in Fig. 2, the red wave being inaudible to the user and the blue wave returns from the wall as an acoustic signal. It is possible to calculate and affect the spatial behavior of sound by accounting for the time intervals between sonic signatures (Haberken 2012). The original version of parametric speakers is the Audio Spotlight by Holosonics, invented in the late 1990's by Joseph Pompei (1997).

Figure 2: *Echolocation Headphones*: Sound Interaction

The speaker used in the *Echolocation Headphones* device is the Japanese TriState (2014a) single directional speaker. It has 50 ultrasonic oscillators with a transmission pressure of 116bB (MIN) and a continuous allowable voltage at 40 kHz of 10 Vrms. The transducer model is AT 40-10PB 3 made by Nippon Ceramic Co, and they have a maximum rating of 20 Vrms (TriState 2014a). These transducers are mounted on a printed circuit board (PCB) board and connected to the driver unit. The driver includes a PIC microcontroller and an LMC 662 operational amplifier. The operating voltage for this circuit is 12 V, with an average of approximately 300 mA and a peak of about 600 mA. It has a mono 1/8'' headphone input compatible with any sound equipment. The sound quality outputted from the Tristate parametric speaker is in the audio frequency band between 400 Hz and 5 kHz. The sonic range of the speaker is

Figure 3: First Iteration of the *Echolocation Headphones* with Augmented False Auricles.

detectable from tens of meters (TriState 2014b).

This device is battery operated with a lithium cell of 12 V and 1 A, kept in a plastic enclosure with an on/off switch attached to the back of the strap of the welding goggles. The battery enclosure and the driving circuit are connected to an MP3 player or another sound outputting device, which could be a computer or a Bluetooth sound module. The electronics of the driving circuit are exposed; however, there is another version of these headphones that include two rounded and concave plates that are placed behind the ears of the wearer to which the driving circuit is attached and concealed (Fig. 3). This auricle extension had a sonic amplification effect and helped the recollection of sound. An echolocation expert mentioned that the plates prevented him from perceiving the sound from all directions, neglecting the reflections behind him, and therefore, this feature was removed.

5.1.1.2 Sound Characteristics

These headphones provide the wearer with focal audition as they scan the surrounding environment. The differences in sound reflection inform a more detailed spatial image. This scanning method is crucial for perceiving the lateral topography of space. The constantly changing direction of the sound beam gives the user information about their spatial surroundings through by hearing the contrast between acoustic signatures. The MP3 player connected to the *Echolocation Headphones* is loaded with a track of continuous clicks and another of white noise. Experimentation and prior art yielded white noise as is the most effective sound for this echolocation purpose. When demonstrating his echolocation method to an audience, Kish (2011) created a ‘‘shh’’ noise to show the distance of a lunch tray from his face. White noise works well, because it provides an extended range of tonality at random; this eases the detection of the level and speed change. Beyond the applicability of navigation, this tool is also useful for differentiating material properties such as dampening.

5.1.2 Experiments: Performance evaluation of Echolocation Headphones

The *Echolocation Headphones* were evaluated quantitatively through three experiments; optimal sound and distance for object location, perceptual resolution by just noticeable difference, and goal-directed spatial navigation for open pathway detection. This device was also evaluated qualitatively in art exhibitions where participants were able to use it freely and asked about their experience in retrospect.

5.1.2.1 Experiment I: Object location: optimal sound type and distance

This first experiment aimed to find the optimal sound type and distance for novice echolocation in detecting an object while using the *Echolocation Headphones*. The participants asked if they perceived an object placed at six distance points from 0 to 3 m in segments of 0.5 m. The three sound types compared were slow clicks, fast clicks, and white noise. Each position was questioned twice for each sound type with a total of 12 trials per sound type and distance point, all totaling 36 trials per participant. This experiment took place at the VR Lab of

Empowerment Informatics at the University of Tsukuba, Japan during July 10th, 12th, and 31st 2016.

5.1.2.1.1 Participants

There were 12 participants between the ages of 22 and 31 with a median age of 23 years old, of which two were female, and ten were male. All the participants reported to have normal or corrected to normal vision, and no participants reported having the previous experience with practicing echolocation.

Figure 4: Object location, Experiment I set-up

5.1.2.1.2 Apparatus

This experiment took place in a room, without any sound dampening, of approximately 4.3 m 9 3.5 m 9 3.6 m. Participants were asked to sit on a chair with a height of 50 cm in the middle of the room and wear the *Echolocation Headphones* device (Fig. 4), which covers their eyes, thus disabling their visual input. The object which they were detecting was a rolling erase board with the dimensions of 120 cm in height and a width of 60 cm. The sounds were created using a MacBook Air 2.2 Intel Core i7 with an output audio sample rate of 44100 with a block size of 64 bits, and the software used was Pure Data version 0.43.4-Extended. The computer was connected to the *Echolocation Headphones* by a 1/8-in. headphone jack in real time.

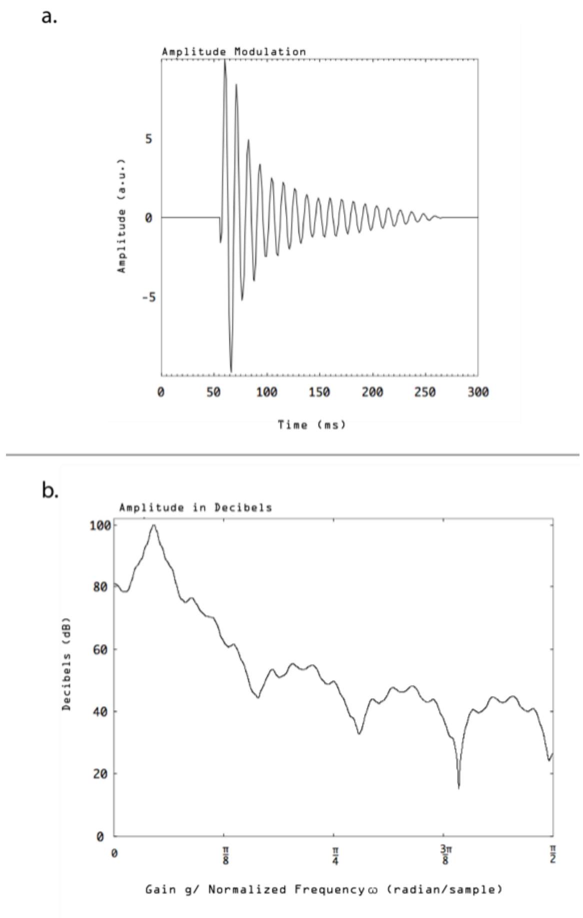


Figure 5: a Amplitude modulation graph of the 4-kHz sound wave decay used for emitting both fast click and slow click sound types (taken from our pure data patch). b Amplitude spectrum in decibels graph (generated with the ‘‘pad.Spectogram.pd’’

5.1.2.1.3 Audio characteristics

The sonic signature for the noise used was a standard noise function of Pure Data (noise *), generated by producing 44100 random values per second in the range of - 1 to 1 of membrane positions (Kreidler 2009). White noise is often used in localization tasks, including devices that guide people to fire exits in case of emergency (Picard et al. 2009).

The sonic signature of the clicks follows some essential features from the samples used by Thaler and Castillo– Serrano (2016) in a study where they compared human echolocation mouth-made sound clicks to loudspeaker made sound clicks. They used a frequency 4 kHz with a decaying exponential separated by 750 ms of silence. Both the fast and slow clicks of our experiment modulate a decaying 4-kHz sound wave with a total duration of 200 and 250 ms of silence separated the rapid clicks and the slow clicks by 750 ms, similar to the experiment mentioned above.

Figure 5a shows the decay of the 4-kHz sound wave created by an envelope generator using an object that produces sequences of ramps (vline *). The series used to generate the envelope was as follows: 10-0-0.1, 5-0.2-0.3, 2.5-0.4-0.6, 1.25-0.8-1.2, 0-2.4-2.4, and 0-0-(750 or 250 depending on fast or slow click). The first number is the amount by which the amplitude increases. The second is the time that it takes for that change to occur in milliseconds. The third is the time that it takes to go to the next sequence from the start of the ramp also in milliseconds, e.g., ‘‘5-0.2-0.3’’ means that the sound will ramp-up to 5 in 0.2 ms and wait 0.3 ms from the start of the ramp (Holzer 2008). Figure 5b shows the amplitude spectrum of the click, both fast and slow, in

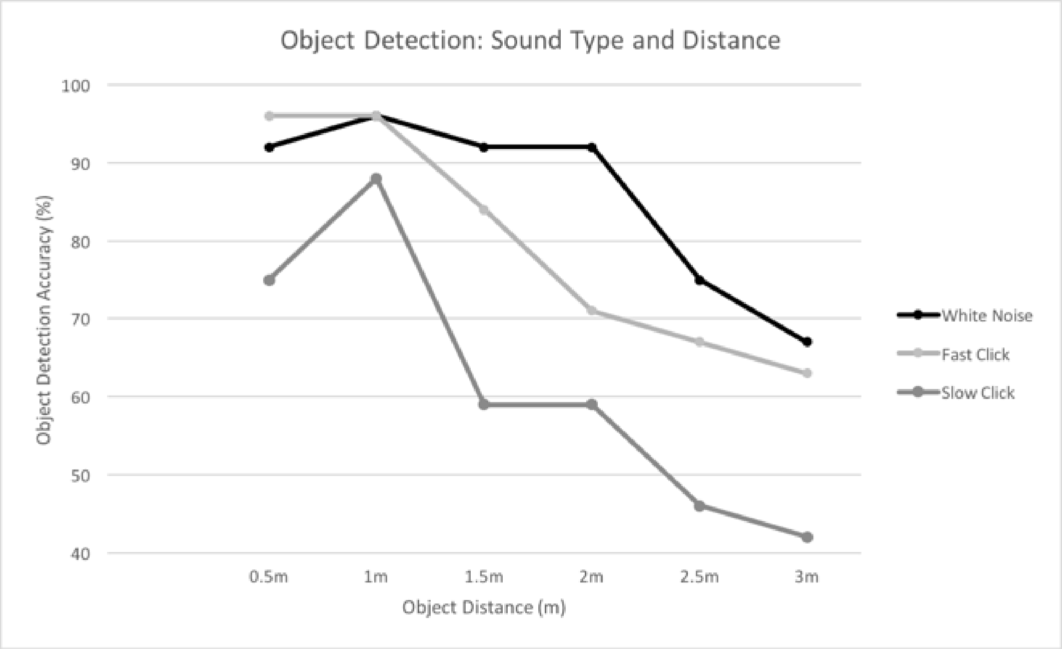


Figure 6: Object detection by distance and sound type graph depicting the object detection accuracy of participants

decibels.

5.1.2.1.4 Procedure

While wearing the *Echolocation Headphones*, the participants were shown the control stimulus, the sound of the room with no object for each of the three sound types. Once the experiment began, they were presented with one of the sound types selected at random to begin the object location task. The participants were asked to reply ‘‘yes’’ if they sensed an object or ‘‘no’’ if they did not sense it.

The board was moved to a distance point chosen at random and each of these distance points was questioned twice. Once all distance points were completed twice, another sound type was chosen at random and the same object location task was repeated. The participants wore noise canceling headphones with music playing at a high volume, adjusted for their comfort, every time that the experimenter moved the object to another location in order to prevent other sonic cues to inform their perception about the location of the object. The total duration of the experiment was between 30 and 45 min, depending on the number of explanations which the participant required.

5.1.2.1.5 Evaluation

The performance accuracy of participants was measured by the number of total correct answers divided by the number of trials per distance point. In this experiment, it is clear that the optimal echolocation distance based on the average performance of 12 participants is between 0 and 1.5 m, 1 m having the best results all sound types (Fig. 6). While the slow click sound type also showed a perceived accuracy average of 88%, it underperformed the other sound types with an average of 64.14%. The performance of participants while detecting the object with fast click sound type had an accuracy average of 96% for both 0.5 and 1 m, with an overall performance accuracy average of 80.14%. The noise sound type outranked all other sound types with a performance accuracy average of 85.67%, with the best detectable range being 96% at 1 m of distance location, while 0.5 m and 1.5–2 m of 92% of performance accuracy average.

5.1.2.2. Experiment II: Just noticeable difference

The goal of this experiment was to find the perceptual resolution of the *Echolocation Headphones* by measuring the sensed difference of distance between two planes through a just noticeable difference (JND) standard procedure.

The experiment was conducted for two reference distances, standard stimuli, of 1 and 2 m. For each reference distance, the object on the right remained in a static position (1 or 2 m) from the participant and the second object was moved back-and-forth. The moving object (MO) started at either 20 cm less or 20 cm more from the static object (SO) (e.g., static object at 1 m; moving object at 1.20 or 80 cm). The starting distance of the MO was selected at random from the above-mentioned starting points and was moved in increments or decrements of 2 cm. This experiment was conducted at the VR Lab of Empowerment Informatics at the University of Tsukuba, Japan in April 11th, 20th, and 30th 2017.

5.1.2.2.1 Participants

There were six participants between the ages of 22 and 35 with a median age of 31 years old, of which one was female and five were male. All the participants reported to have normal or corrected to normal vision. Only three of the participants reported having the previous experience with practicing echolocation, since they had participated once in a previous experiment wearing the *Echolocation Headphones*.

5.1.2.2.2 Apparatus

Figure 7: JND, Experiment II Set-up.

This experiment was conducted in a room without any sound dampening of approximately 4.3m long, 3.5m wide, and a 3.6m height. Participants were asked to sit on a chair with a height of 50 cm a tone of the long ends of a table measuring 1m x 3.4m x 0.76m located in the middle of the room (Fig. 7). The sound was generated from a recorded sound file of white noise, played through an MP3 player connected to a short end-to end headphone jack. The MP3 player was a FastTech mini device with a TransFlash card (miniSD) memory model DX 48426. The objects were two boards of 29.7 cm 9 42 cm of medium-density fiberboard (MDF) in portrait orientation. They included an acrylic stand on the back that allowed them to stand perfectly perpendicular to the table surface.

5.1.2.2.3 Procedure

The participants were asked to wear the *Echolocation Headphones* device, which completely covers their vision. Before the experiment began, the participants, while wearing the device, were showed the control stimuli. The MO and SO at the same distance for each reference point of 1 and 2 m showed the MO at 20 cm further from each reference point and 20 cm closer. The experimenter explained the task to the participants to reply ‘‘yes’’ if they noticed a difference between the two objects or ‘‘no’’ if they sensed no difference. They were also asked to not consider their previous answer, since the objects would be moved at random.

For each task, the participant was asked if they detected a difference in distance between the objects, and depending on their answer, the MO would be moved towards the SO or away from it. If the participant replied ‘‘Yes’’, meaning that they detected a difference, the MO would be adjusted by 2 cm in the direction of the SO, and in the direction away from the MO if they replied ‘‘No’’. The placement of the MO would change at random between the tasks, picking up from the last answer, changing the further starting point and the closer starting point. Once the answers from the participants reached a sequence of five affirmative and negative answers in both directions, the experiment concluded. The total duration of the experiment varied from 30 to 60 min depending on the ability of the participant to sense the different distance between the object.

5.1.2.2.4 Evaluation

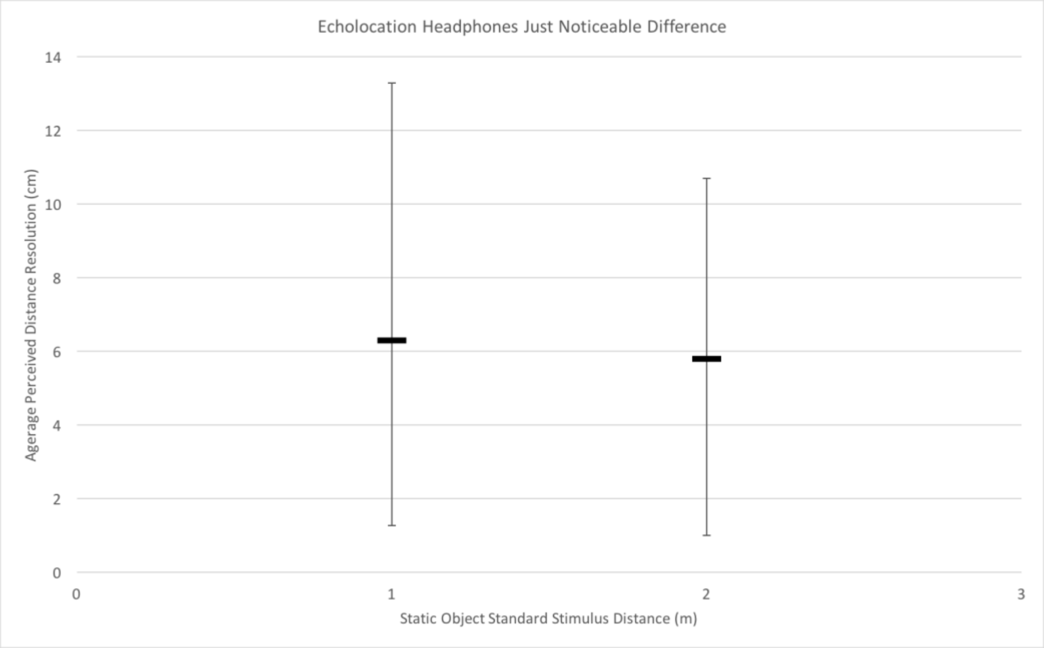


Figure 8: *Echolocation Headphones* just noticeable difference experiment results' graph

The results of the experiment were analyzed by finding the average distance of which the participants sensed the difference between the two objects (MO and SO) (Fig. 8). The final distance of the MO further from the SO was calculated and averaged for all trials, and the final distance of the MO closer from the SO was averaged for all trials. These two averages were then combined returning the final average of perceptual resolution for both constant stimuli of 1 and 2 m. The top standard deviation was selected from the average of the closer MO average, and the bottom was selected from the further average for each of the constant stimuli.

In Fig. 8 above, the average perceived distance resolution for both constant stimuli is around 6 cm from the target distance to the constant stimuli. While there is a slightly more acute resolution for the 2-m constant stimulus, one can observe that the lower standard deviation for both constant stimuli distance points is around 2 cm, which is the shortest distance selected for the experiment as the lowest perceived resolution. As for the top standard deviation, the average for the 1-m constant stimulus is around 13 cm, while the 2-m constant stimulus is around 11 cm. It can be concluded that there is a slight acuity gained from sensing the distance between objects at 2 or 1 m. However, the difference is very small, almost negligible, therefore, concluding that there is a 6-cm perceptual resolution for distances between 80 and 220 cm.

5.1.2.3 Experiment III: Task-oriented path recognition

The aim of this experiment was to measure the ability of participants to find an open path while wearing the *Echolocation Headphones*. The experiment was set in a hallway where participants walked while scanning their surroundings with the objective to find an open door. There were three doors used in the experiment located at various placements along the way, which could be open or closed in random combinations for each trial of one, two, and three open doors, a total of three trials per participant. This experiment was conducted at the VR Lab of Empowerment Informatics at the University of Tsukuba, Japan in May of 2017.

5.1.2.3.1 Participants

There was a total of six participants between the ages of 24 and 35, with a median age of 31 years old, of which three were female and three were male. All participants reported having normal or corrected vision to normal. Of the six participants, only three participants had the previous experience with echolocation while wearing the *Echolocation Headphones*.

5.1.2.3.2 Apparatus

Figure 9: Open path recognition, Experiment III set-up

The experiment was conducted in a hallway with concrete floors, MDF board walls, and a metal flashing ceiling with exposed fiber insulation bags. The hallway was not fitted with any kind of sound dampening materials, and its measurements were around 10 m 9 1.4 m 9 3.6 m (Fig. 9). The sound was generated from a recorded sound file of white noise, played through the same FastTech mini MP3 player, model DX 48426, of the previous JND experiment. The doors to be located were around 1-m width and 2.1 m in height.

5.1.2.3.3 Procedure

The participants were asked to wear the *Echolocation Headphones*, which completely cover their vision. The participants, while wearing the device, were showed the control stimuli and a sample of the task. They stood in front of a door which was open and then guided towards the wall where there was no wall to sense the audible difference between an open path and a wall obstruction. They were given the freedom to move from side to side towards the open path and the obstruction.

Once they felt comfortable with their ability to deter- mine the difference in stimuli, the experiment began and received the instructions for the experiment. They were asked to walk through the hallway, slowly scanning their surroundings. They were given two options on how to scan the hallway. One way was to walk sideways scanning one wall first and then the opposite wall on their way back from the end of the hallway. The second option was to scan the hallway by turning their head from left to right, back-and- forth, seeking the feedback of each side one step at a

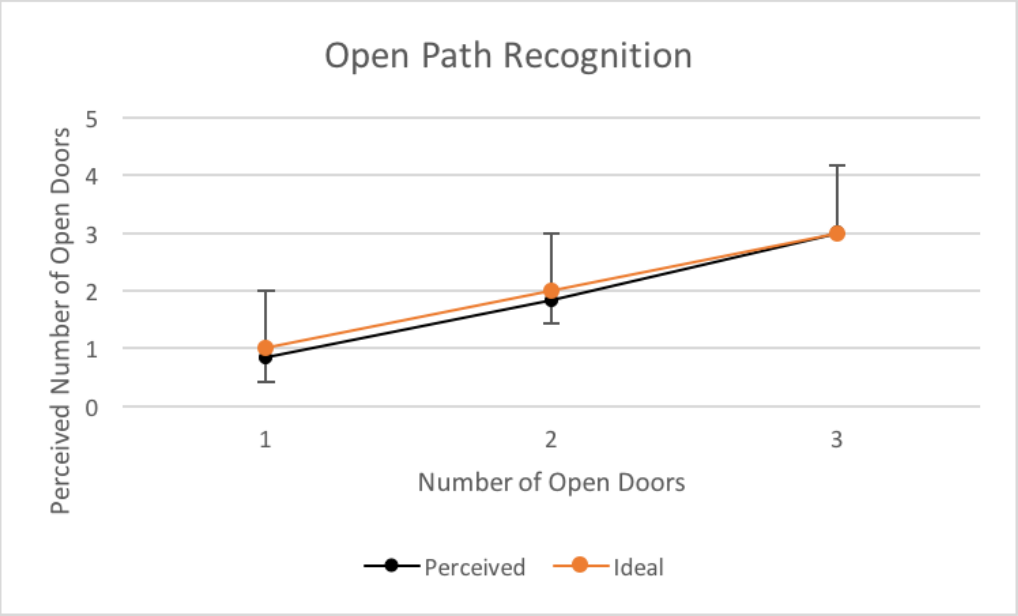


Figure 10: Open path recognition, perceived number of open doors experiment results graph

time. The participants were given this freedom to slow their walking speed, because by walking forward too quickly missed a few cues. Once their walking style was determined, they were asked to find the open doors and to point in its direction saying ‘‘This is an open door.’’ Each participant was tested through three trials for each combination of one, two, and three open doors selected at random.

5.1.2.3.4 Evaluation

In the Open Path Recognition graph in Fig. 10, the average of perceived open doors is very close to the ideal number of perceived open doors. This means that the participants were able to assess accurately the difference from a path and an obstacle. The top margin of error is the average number of false doors that were perceived for all trials, while the bottom standard deviation was retrieved from the number of doors that participants failed to recognize for each trial.

Of all participants, only two perceived phantom doors. While observing their behavior, it can be determined that those false positives were due to their scanning of the wall at an angle, meaning that the angle provided them with a decrease in volume from the echoing signal, which they had already associated with an open path. This phenomenon should be addressed as it dampens the performance of participants wearing the tool, albeit only a few of them were unable to detect the difference from an open door and an angular reflection of the returning signal. Beyond this anomaly, the overall average performance of the participants was almost perfectly in line with the ideal performance. It can be concluded that the *Echolocation Headphones* is a helpful tool for aiding navigation in circumstances where audition is required and vision is hindered.

5.1.3 Social evaluation: art exhibition interactions and feedback

The *Echolocation Headphones* has been shown in different kinds of settings, from museum installations to conference demonstrations. It has also been tested by a wide range of participants, who through playful interaction gain a new perspective on their spatial surroundings.

5.1.3.1 Novice echolocation behaviors

During most of the exhibition settings, attendants were invited to try the *Echolocation Headphones*. Each time, the device was always paired with an audio player, either a cell phone or an MP3 player. The sound was always white noise, either from an MP3 file or a noise generating application such as SGenerator by ScorpionZZZ’s Lab (2013). These exhibiting opportunities allowed for *Echolocation Headphones* to be experienced in a less controlled environment than the lab experiments.

Participants were given simple guidelines and a basic explanation of how the device functions. In this informal setting, the behavior of participants was similar and they were usually able to identify distance and spatial resonance within the first minute of wearing the device. They would often scan their hands, walk around, and when finding a wall, they would approach it closely, touch it, and gauge the distance. After wearing the device for a while longer, they became more aware of the sonic signatures of the space around them, navigating without stumbling with object in their direct line of ‘‘sight.’’ Their navigation improved when they realized that the side-to-side and back-and-forth scanning technique was necessary to gather distance differential. This is a similar movement performed with the eyes, also known as saccades. Without these movements, a static eye cannot observe, since the fovea is very small. This is the part of the eye that can capture in detail and allow for high-resolution visual information to be perceived Iwasaki and Inomara (1986). The scanning behavior was helpful for most situations, but given that the field of ‘‘sight’’ from the device is narrower than that of actual sight, there were some collisions. When there were objects in the way of participants that did not reach the direct line of the sound beam, such as a table which is usually at waist height, they would almost always collide with it.

Figure 11: Exhibition showing the material differentiation task at the EMP Open Studio, Tsukuba, Japan

In one of the art exhibitions, the device was shown alongside three rectangular boards of acrylic with a thick- ness of 2.5 mm, corrugated cardboard of 3 mm, and acoustic foam with an egg crate formation of 30 mm (Fig. 11). From observation, participants were able to distinguish materials based on their reflection using sound as the only informative stimuli. They were most successful in finding the acoustic foam naturally, since its sound absorption properties of this material are very porous and specifically manufactured for this purpose. Participants are able to detect the difference of materials based on the intensity change of the sound when echolocation is performed, the intensity of the audible reflection is crucial for gathering the properties of the target in space.

5.1.3.2 Participant feedback

The participants' comments when experiencing the *Echolocation Headphones* were mostly positive, e.g., ''The device was efficient in helping navigate in the space around me without being able to actually see.'' and ''It indicates when an object is nearby that reflects the sound back to the sensor.'' Another participant had an observation pertinent to the theories that apply to sensory substitution and brain plasticity where these phenomena happen through a learning process and practice. This participant stated — ''It was interesting to listen to, I think it would take time to be able to use it effectively and learn to recognize the subtle details of the changes in sound''. When participants were asked about the white noise generated by the device, they stated —''It actually becomes comforting after a while, because you know it's your only way of really telling what's going on around you''. Another comment was more direct stating that the sound was ''Pretty annoying''. While white noise is very effective for audio location purposes, it can be jarring because of its frequency randomness. However, one participant noted a wonderful analogy from noise to space. He said that ''In blindness, one can finally see it all when it rains''. He meant that the noise of the seemingly infinite drops of rain falling to the ground creates a detailed sonic map of the environment.

5.1.4 Echolocation Headphones Conclusion

The *Echolocation Headphones* device is a sensory substitution tool that enhances human ability to perform echolocation, improving auditory links to visuospatial skills. They are an Assistive Device artwork, designed within the interdisciplinary lines of engineering and art. This device shines a new light on AT and its user base expansion. It brings interaction, playfulness, and perceptual awareness to its participants. This concept popularizes and makes desirable technology that could prove useful for the blind community; however, it is designed to be valuable and attainable to everyone.

From an engineering perspective, this device presents a novel application for parametric speakers and a useful solution for spatial navigation through the interpretation of audible information. Utilizing the parametric speaker as an echolocation transducer is a new application, because these speakers are typically used to contain and target sound towards crowds. They usually are audio information displays for targeted advertising. This prototype also takes into account a trend within the study of perception, which is considering a multimodal perspective in contrast to the reductionist approach of studying sensory modalities independently.

The *Echolocation Headphones* have been designed not to focus on the translation of visual feedback directly into sound, but rather as a tool that enhances the multimodal precept of space. This tool re-centralizes the user's attention from gathering audible instead of visual information to determine their location. Thus, their spatial perception remains the same; however, it arrives through a different sonic perspective. The *Echolocation Headphones* have been evaluated with psychophysical methods to investigate their performance and perceptual cohesion. According to the data gathered through the multiple experiments and exhibition demonstrations, the feasibility of sonic visuospatial location through the *Echolocation Headphones* as a training device for sighted individuals is positive. Utilizing sound as a means of spatial navigation is not imperative for sighted subjects, but this tool shows that the experience of sensory substitution is possible regardless of skill. This prototype exemplifies the ability and plasticity of the brain's perceptual pathways to quickly adapt from processing spatial cues from one sense to another.

5.2 *IrukaTact*: A Parallel Sense of Touch Underwater

The motivation behind this case study is to develop a wearable device for underwater haptic stimulation and to understand the perceivable range for this tool as a tactile display, as well as pairing this device with a sonar sensor for haptic rendering of underwater topographies. The mechanoreceptors on the volar pad of our fingers are very sensitive to light touch, and by using the viscosity of aqueous environments to propel force feedback, these haptic modules display a detectable mixture of vibration and pressure. The *IrukaTact* haptic probe uses a motor to collect water from its surroundings that is digitally controlled by a Pulse Width Modulation (PWM) signal. This signal varies the speed of a stream that disembogues through a small channel, pressurizing water onto the finger pads as shown in Figure 1. The sensation of this pressure is similar to placing a finger under a tap of running water. This sensation is a desirable quality in the attempt of artificially rendering tactile information, much more than vibration alone. *IrukaTact* has an inherent vibration due to its motorized mechanism. The aim of this device is to focus on selectively stimulating the mechanoreceptors of the skin, and providing slight muscular and skeletal pressure. The design of this device takes into account the need for rendering new types of haptic feedback. Vibrotactile stimulators are widely used, and according to Dr. Iwata (2008), they are relatively easy to produce. Vibrating motors are the most commonly utilized method for wearable haptic displays, often serving as a means of signaling such as alert tones. However, there are many other types of selective skin stimulation, such as electrode, ultrasonic, and air jet displays with the purpose of recreating virtual texture and an object's surface (Iwata 2008).

This section discusses the design process of this new underwater haptic actuation technique, the aesthetic sensibility and technical implementation for creating this tool considering its wearability and modular design. Furthermore, it describes a series of experiments that test the module's performance. The firsts two experiments yielded that the haptic module propelled approximately 0.9 L/min at is maximum speed and a force of 4,21005.84 N. Its display performance was tested by searching for the absolute threshold and the haptic perceptual resolution of user while wearing the device. The experiments conclude with an adaptation of the *IrukaTact* module that includes a sonar module, testing the user's perception of distances inside of a pool and rendered underwater. User feedback was collected from various demonstrations and exhibitions where the *DemoTank* units were presented. Lastly, it discusses the next steps for improving this tool as an echo-haptic glove for future applications of this technology as an assistive aid.

5.2.1 Underwater Haptics Prior-Art

Emerging techniques for haptic actuation with liquids have a high potential for virtual reality among other applications. While vibration devices can easily become waterproof, utilizing water pressure as a medium to be sculpted by reactive systems can result in richer experiences for touch. Researchers are working with liquids for haptic feedback in different capacities. Some are activating the user's sense of touch with liquids in a dry environment, such as *LiquidTouch*, a typical touchscreen interface with a mounted water jet that sprays water, similar to a water gun, onto the user's finger to reaffirm activation of the screen (Richter 2013). *Jorro Beat* is a similar haptic interface which synchronizes music beats to water modulation from a shower head, using the water spray to convey and enhance other information such as sound modulation (Hoshino 2015). Another interface is Yoshimoto's (2010) *Haptic Canvas*, which similarly projects colors onto a tub of starch and water mixture, a non-Newtonian fluid, as a control method to change the viscosity of this particular fluid with a suction device attached to the fingertip. While Yoshimoto's interface is wearable, it relies on the properties of a specific fluid mixture and thus can only be used in a vat of this specific liquid. Another tub oriented interface created by Nakamura (2014) utilizes electric polarity to simulate direction and stimulus orientation using electric plates attached on four quadrants of a cylindrical reservoir of water. The *IrukaTact* fingertip haptic modules are wearable and are not limited to a specific liquid substance. They are useful in any aquatic environment, from a vat, to a pool of water, or any other liquid, provided that it has a similar viscosity to water.

Furthermore, translating visuospatial information to haptic feedback, similar to the *IrukaTact* glove application, can be seen in the work of Cassinelli (2006), Haptic Radar, where ultrasonic probes placed around a headband inform vibrotactile actuators placed beneath each sensor, giving the user a surround haptic display of range data. Haptic feedback has also been used to enhance visual bathymetry map data by mapping the elevation change of the ocean floors to color indicators and to the *StickGrip* haptic device (Evreinova, et Al 2012). Using this visuo-tactile hybrid method they were able to gain higher accurate navigation by 14.25% to 23.5% in a range of bathymetric data of 40- 140m (Evreinova, et Al 2012). These submersible haptic modules contribute to the advancement of underwater haptic actuators, and they are innovative in their design to be wearable, as well as providing non-restrictive force feedback with a mixture of vibration stimulation.

5.2.1 Device Design

Beyond its utility as an underwater display tool and its utilitarian applications, this work is an artistic exploration, a piece of Assistive Device Art (ADA). Which comes from the Japanese movement of Device Art led by Dr. Hiroo Iwata (2014), which is a form of art blended within the fields of engineering and informatics, taking into account the commercial capacities of digital reproduction. Device Art and ADA are not always created with the purpose of commercialization, but rather these works function in transcendence, providing more questions and inspire new possibilities beyond the pure utility of devices. Assistive Device Artworks are suspended between the utilitarian purpose of technology, the drive for augmenting human abilities, and augment creative perspectives to learn about our own physiology. *IrukaTact* strives to cultivate the drive for the curiosity which helps us better understand the impact and unwitting applications of technology that assists humans to further develop their senses underwater.

5.2.1.1 Aesthetic Design

Aesthetic sensibility was carefully considered for the design of this tool as much as the design of its functionality and usability. The look and feel of the tip design bridges the interest of people who are not familiar with haptic technology, and thus promotes haptic technology to a broader public. The visual design of this tool was inspired by its name 'iruka', (イルカ) dolphin in Japanese, and the look of jetpacks and other missile style devices.

5.2.1.2 Mechanism

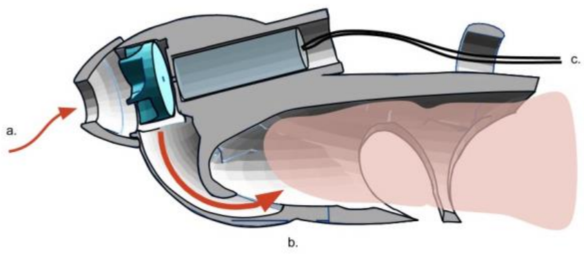


Figure 12: Cross-section diagram of the *IrukaTact* haptic module mechanism.

This fingertip haptic module is designed to house a small motor placed on top of the finger (Figure 12), and it's equipped with an impeller tip that suctions water from the surrounding environment entering through port (a) as depicted on Figure 12. The water is propelled through a channel that disembogues on to an opening (b) directed to the volar pad of the fingertip. The motor has a voltage of DC 3.7V no-load quiescent current: 0.04A, the no-load rotational speed: 46000 ± 10% rpm, stall torque: 8g * cm, stall current: 1A, noise: 78dB, below vibration: 0.2cm/s or less, and its total length including the axis is: 18.4mm. Its speed is controlled with an ATmega 328PU Arduino UNO microcontroller and through a PNP 2222 transistor. The maximum voltage at which the motor can operate while submerged underwater is 5.39 V. The cable connections are run through a waterproof protective silicone tube that passes through a holding ring as shown in Figure 12 (c), which fastens the cable comfortable over the finger. The fingertip haptic module has been designed using a 3D CAD online platform and printed with a high quality PolyJet 3D printer, which produces waterproof models. Attached to the motor is a small impeller that suctions the surrounding water. For the syphoning mechanism, the six-blade impeller in Figure 13 is of 1 cm^2.

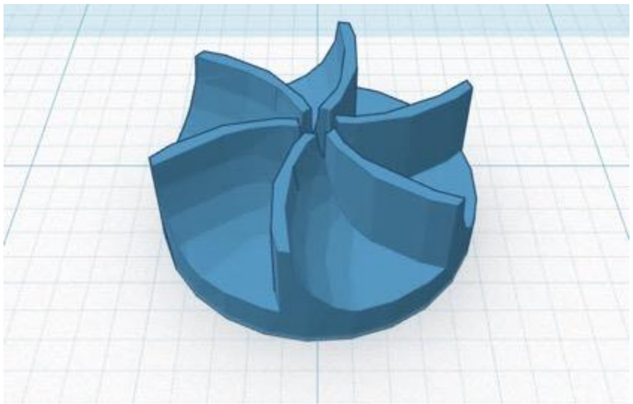


Figure 13: Six Blade Impeller Attachment for the Motor

An underwater camera captured the suction mechanism of the fingertip module by letting a denser liquid settle to the bottom of a water bowl. Figure 14 shows the plume of the darker soy sauce entering the haptic module through the impeller pump opening. The soy sauce was used for demonstration of the suction mechanism for purposes only, even though the device uses the surrounding water during normal use.

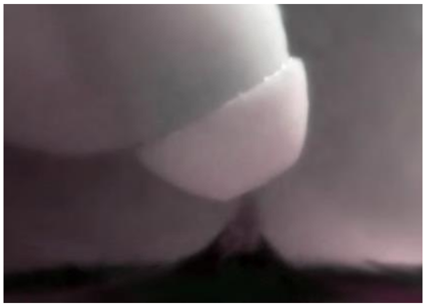


Figure 14: Impeller fingertip suctioning denser liquid on the bottom to illustrate the function of the pump.

5.2.1.3 Prototyping Feel

The process of ideating new ways to translate haptic actuation yielded various models that could apply pressure, vibration, and displacement underwater. Figure 15 demonstrates the various iterations that were generated while prototyping the size of the fingertip haptic modules, the left most design on this image is the first iteration of the thimble housings.

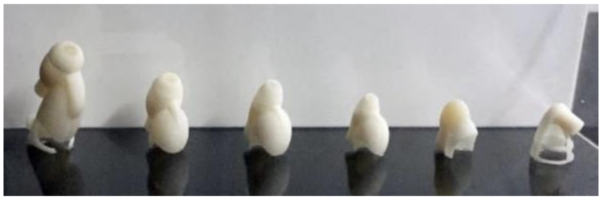


Figure 15: Impeller Model Haptic Actuator Evolution

Three kinds of thimble finger housings were designed to distinguish between usability and actuation effectiveness of the motor placement (Figures 16, 17, 18). Under limited, intuitive testing of these fingertip housings, the results were that the underbelly model (Figure 16) was the most effective in terms of sensory actuation, providing a strong signal of both vibration and force, but the placement of the motor under the finger would intervene with the user’s grasping functions. The vertical

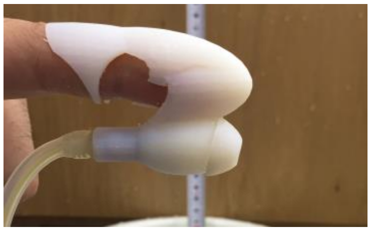


Figure 16: Underbelly impeller fingertip thimble housing.

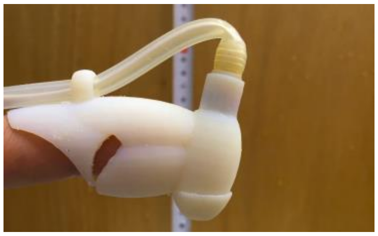


Figure 17: Cricket, vertical motor impeller fingertip actuator housing.

Figure 18: *IrukaTact* original top impeller fingertip thimble housing.

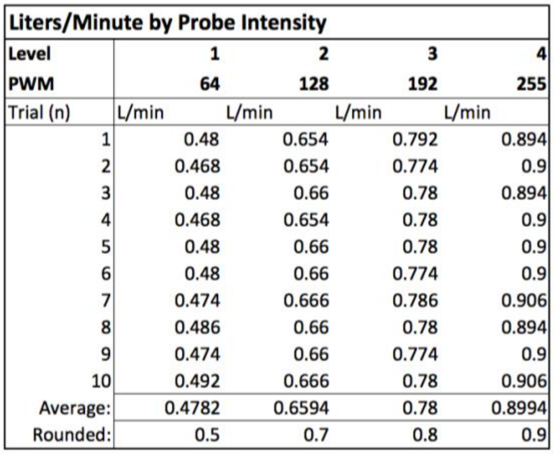
motor placement model (Figure 17) was the least effective in terms of haptic actuation, and its design would also impede the user's grasping movements. Finally, the top motor placement (Figure 18) provided a compromise between maximum usability, comfort, and sufficient haptic actuation, even though the underbelly model had a more effective haptic actuation of the three models.

5.2.2 Experiments

While the motor placement and thimble housing design was an intuitive process of usability and comfort, the accuracy of signal perception was tested through a series of experiments, one searching for the force display performance, and three perceptual studies of absolute threshold (AT), haptic resolution, and distance detection and approximation.

5.2.2.1 Experiment I: Liters/min Feedback

This experiment seeks to assess the force feedback of the *IrukaTact* haptic module. These experiments were conducted at the EMP VRLab, of the University of Tsukuba, Japan. A new version of this module was created where the disemboguing channel of the device is connected to a silicone tube with an inner circumference of 3mm. The maximum motor speed of the module was divided in five intensity levels (0-5) yielding the following PWM values: 0, 64, 128, 192, and 255 and voltages of: 0 V, 1.80 V, 2.94 V, 4.27 V, 5.39 V.



Liters/Minute by Probe Intensity

Level	**1**	**2**	**3**	**4**
PWM	**64**	**128**	**192**	**255**
Trial (n)	L/min	L/min	L/min	L/min
1	0.48	0.654	0.792	0.894
2	0.468	0.654	0.774	0.9
3	0.48	0.66	0.78	0.894
4	0.468	0.654	0.78	0.9
5	0.48	0.66	0.78	0.9
6	0.48	0.66	0.774	0.9
7	0.474	0.666	0.786	0.906
8	0.486	0.66	0.78	0.894
9	0.474	0.66	0.774	0.9
10	0.492	0.666	0.78	0.906
Average:	0.4782	0.6594	0.78	0.8994
Rounded:	0.5	0.7	0.8	0.9

Figure 19: Liters per Minute Data Table.

First, the liters per minute were calculated, this was done setting the tube to discharge in a cup measuring milliliters. Each speed level was tested ten times in order to record the average liters per minute. This was done by programming a timer of 10 seconds and recording the amount of water released in each trial. The averages for each level are found in the data table of Figure 19. Thaptic module propels approximately 0.9 L/min at is maximum speed.

5.2.2.2 Experiment II: Force Feedback

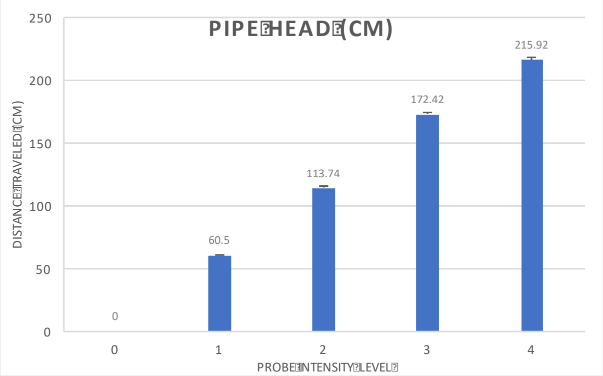


Figure 20: Pipe Head Data Table.

Once the pipe head for each five levels was averaged, we used the following formula to deduce the force applied to the fingertips:

The force feedback of the module was calculated by fastening the tube to a wall at a height of 4m, with the module submerged in a tank of colored water below it. A measuring tape was then placed next to the tube. Each of the same levels were assessed five times. This was done by letting the liquid reach its stable height within the tube and recording this height in cm and averaging the pipe head results shown in Figure 20.

$$P_{\text{fluid}} = r\ g\ h = (1.00\ \text{x}10^{3}\ \text{kg/m}^{3})\ (9.8\ \text{m/s}^{2})$$

$$(\text{m}) = \text{Newtons/m}^{2}$$

In this formula, we calculate the pressure of the water by multiplying (r • g • h), where *r* is the fluid density of water, times *g* which is gravity, and *h* which is the height in meters where the fluid stabilized at each of the five intensity levels of the module yielding the results of the applied force in Newtons/m^2, yielding a maximum force of 21,005.84 N/ m^2, and can be observed in Figure 21.

5.2.2.3 Experiment III: Absolute Threshold

The first haptic perception experiment conducted was the absolute threshold test. This test allowed us to understand the minimum stimuli for signal detection, more specifically at which PWM point can 100% of the participants perceive a stimulus at all. This

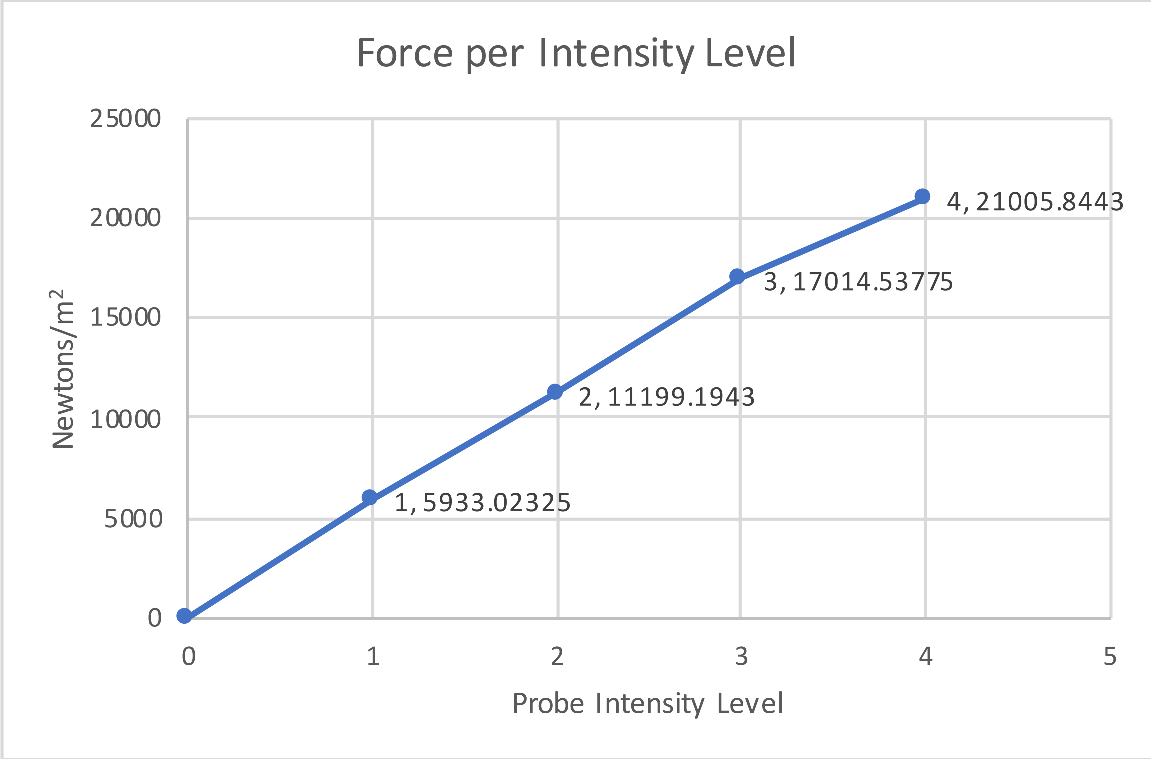


Figure 21: Pressure Force Feedback Data Table.

experiment was conducted at the EMP VRlab at the University of Tsukuba, Japan.

5.2.2.3.1 Participants

There were seven participants from the ages of 22-35, with a median age of 24 years old, two of which were females and five of them were males. All subjects participated in one trial each, and three of them participated in two on their own accord. All of the participants were new to this probe, and were first time users. They were free to undergo the experiment with the hand and finger of their choosing. There was a total of 10 trials for this experiment.

5.2.2.3.2 Apparatus

The experiment consisted on an array of randomly sequenced signals from 0 to 64 PWM, forces of 0-5933N/ m^2. The maximum signal point was selected from 5933N/ m^2 being the highest force of the first quarter of the maximum intensity of the motor, which is 255PWM (4,21005.84 N/ m^2). The signals were produced by a testing module, which consisted of an Arduino UNO, one PNP 2222 transistor, the *IrukaTact* haptic module, and one button which when pressed would provide the next random PWM signal. The signal had a time limit of 1000ms, after which the signal

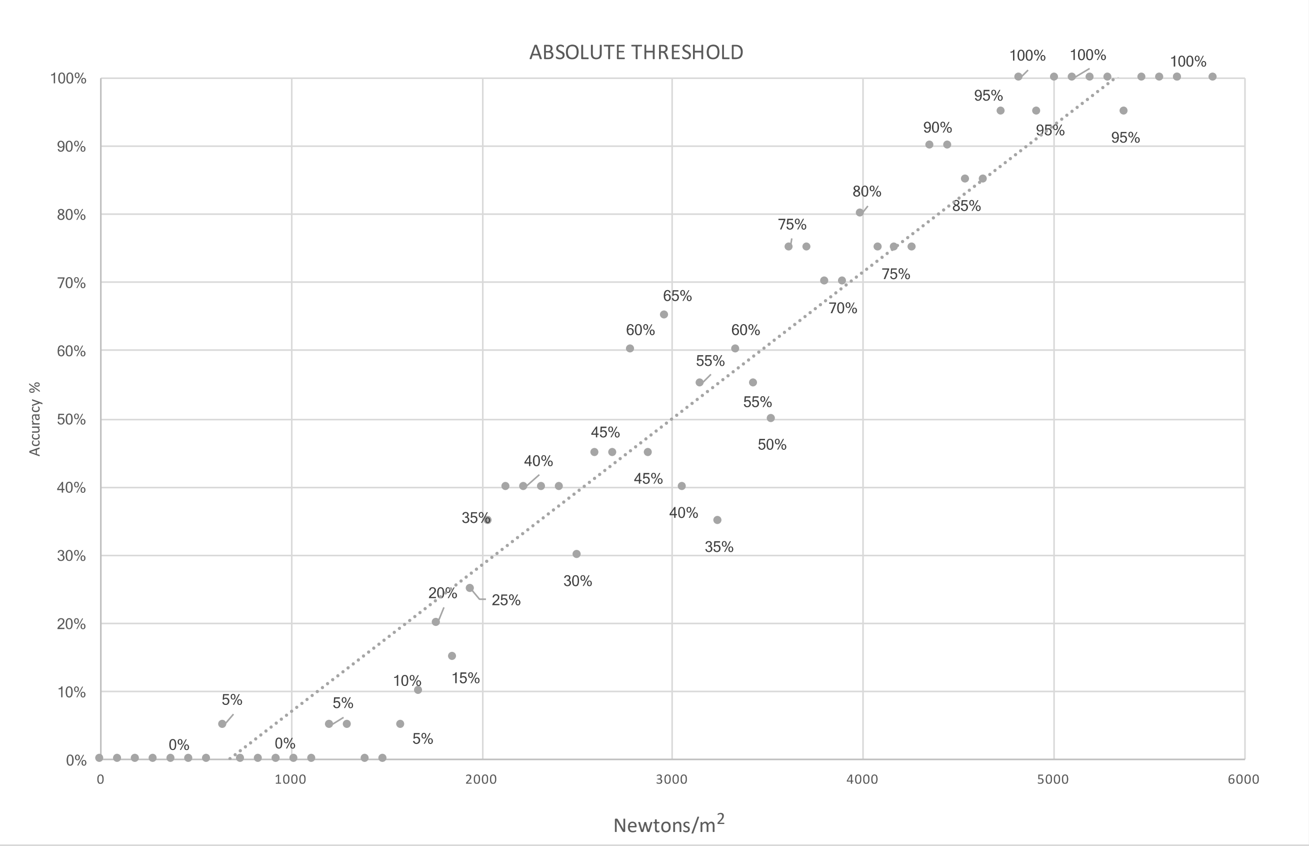


Figure 22: Absolute Threshold results.

would revert to 0 until the button was pressed again. The data from this experiment was recorded through the serial port, inscribing the PWM point in question as well as a '1' if the participant claimed a sensation and a '0' otherwise.

Each user was asked to wear the submersible haptic module on their finger and insert it inside a bowl of water in front of them. The participant was asked to say 'yes' if they felt a signal and 'no' if they could not feel anything. Each signal point was tested twice for each trial.

5.2.2.3.3 Results

There is a 50% signal perception rate between 2873.79 N/ m^2 (31 PWM) and 3615.42 N/ m^2 (39 PWM). There is a 95% consensus on the perception of the signal at both 5005.96 N/ m^2 (54 PWM) and 5469.48 N/ m^2 (59 PWM). It is our conclusion that the absolute threshold is 5562.18 N/ m^2 (60 PWM), with a 100% of participant affirmation for this stimulus (Fig. 22).

5.2.2.4 Experiment IV: Haptic Resolution

This experiment consisted of finding participants' haptic resolution while wearing the probe, with the aim to understand how many pressure values a participant can differentiate at random. The fingertip haptic actuator module can provide a maximum force of 4,21005.84 N/ m^2 divisible by 256 values of PWM from 0-255, but unless the signals are sequentially increasing or decreasing most users may have trouble distinguishing between intensities. Hypothetically a participant can distinguish between three intensities: none, low, and high; however, we were interested in learning whether a participant could distinguish between five different signals at random. This experiment was conducted at the Art|Sci Center at the University of California, Los Angeles, U.S.A.

5.2.2.4.1 Participants

For this experiment, we had 11 participants from ages 16-37, with a median age of 20 years old. There were four females and seven males, and all of them used the hand and finger of their choice. All of the participants were new to this haptic module, and were first time users. The participants were volunteers from a summer program at the university.

5.2.2.4.2 Apparatus

The signals to be presented in random order were chosen from the same five levels used in the liters/minute and force feedback experiment. These five levels were displaying forces of: 0 N/m^2, 5,933.02 N/m^2, 11,199.19 N/m^2, 17,014.53 N/m^2, and 21,005.8443 N/m^2. The different signals were produced by a testing module that contained five buttons, one for each signal. The signal was not timed; they were produced continuously until the conductor changed to a new signal.

Each participant was asked to wear the submersible haptic module on their finger and insert it inside a large tank of water sitting beside them at arm's length. They were first shown the five different levels in a sequence increasing from 0 to maximum, and then decreasing in reverse order, and asked to say 'OK' every time they felt the level change. Once each participant was comfortable in distinguishing between the five different levels sequentially, we proceeded to administer the levels at random twice for each intensity level

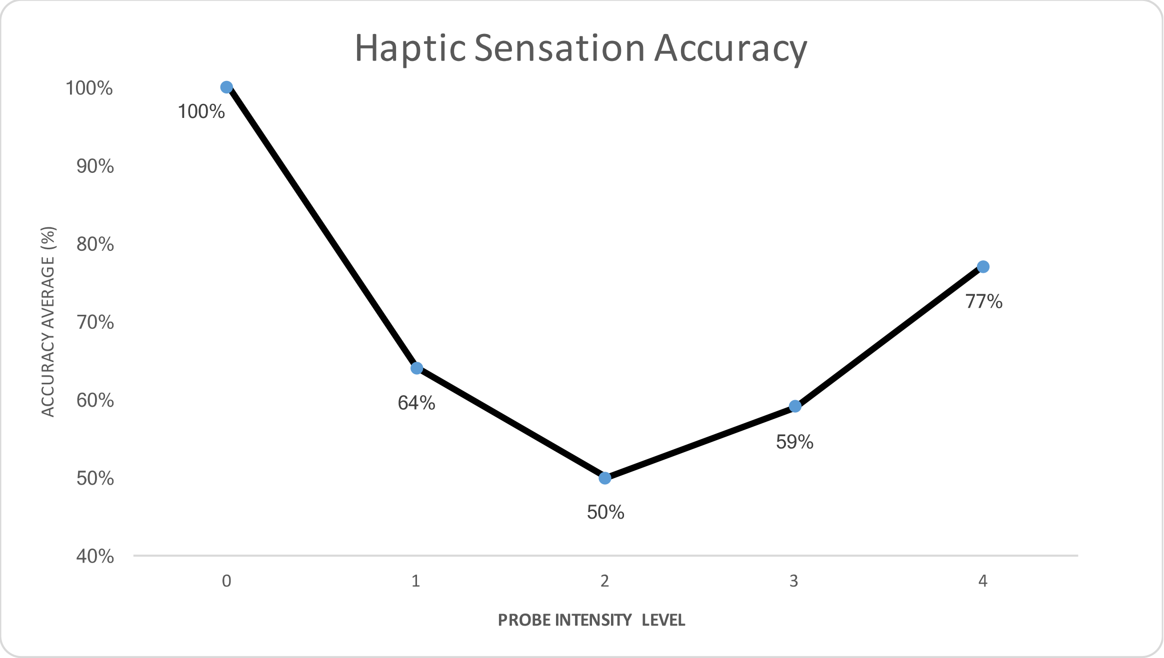


Figure 23: Haptic Resolution Accuracy

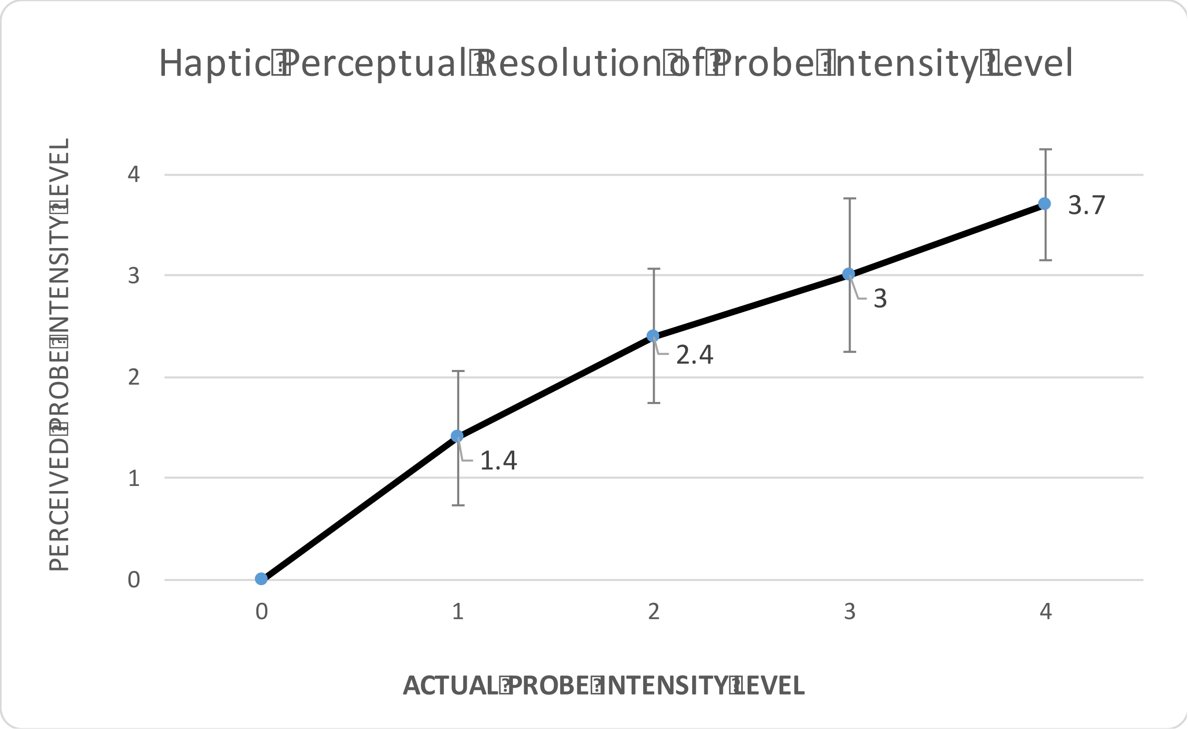


Figure 24: Haptic Resolution: Perceived Intensity Level

they were feeling from 0 to 4.

5.2.2.4.3 Results

There were 22 trials for each of the five levels in question. Figure 23 shows the average accuracy percentage of all trials for each of the intensity levels presented during the experiment. The highest accuracy of 100% was achieved at 0, every participant was absolutely certain that there was no sensation at all. The second highest accuracy rate of 77% was achieved by the most intense level 4 of 21,005.8443 N/m^2 (255 PWM). Levels 1 through 3 presented less accuracy, the median level 2 of 128 PWM being the least likely to be detected accurately at 50%.

Figure 24 demonstrates that participants tend to aim higher for levels 1 and 2, with an average of 1.4 for level 1, and 2.4 for level 2. Level 3 has the highest accuracy average, and as for level 4 participants aim lower with an average of 3.7. This experiment concludes that most participants could discern the difference between none, low, and high, while still having trouble understanding the difference between levels 1-3. At the end of each trial participants were asked to elaborate on their experience, and to describe whether it was easier to know the level of intensity while it was presented to them in a descending or ascending sequence. All participants, except for one, agreed that presenting the stimulus sequentially would be more helpful. One participant added – '[It would be] more dramatic if it was in all your fingers. The jolt between the levels is also helpful,' referring to the motor quickly turning levels without a smooth transition.

5.2.2.5 Experiment V: Distance Assessment

The aim of this experiment is to assess the performance of this haptic probe while displaying linearly mapped data from an ultrasonic range-finder. The goal was to find whether participants were able to distinguish between distances, and gauge the meters of length they were sensing. It evaluated whether the *IrukaTact* haptic display can be useful for an echo-haptic application, and give users a parallel sense of touch underwater. This experiment was conducted at the athletic pool of half-Olympic size at the University of Tsukuba.

5.2.2.5.1 Participants

There were seven participants of the ages (24-35) with a median age of 26 years old. Two of the participants were female and the rest were male. Four of the participants were new to this probe and three had participated in previous experiments.

5.2.2.5.2 Apparatus

Figure 25: *IrukaTact* Sonar Tip

There were two experimenters, one which assisted the participants inside of the pool, and another which recorded the participant

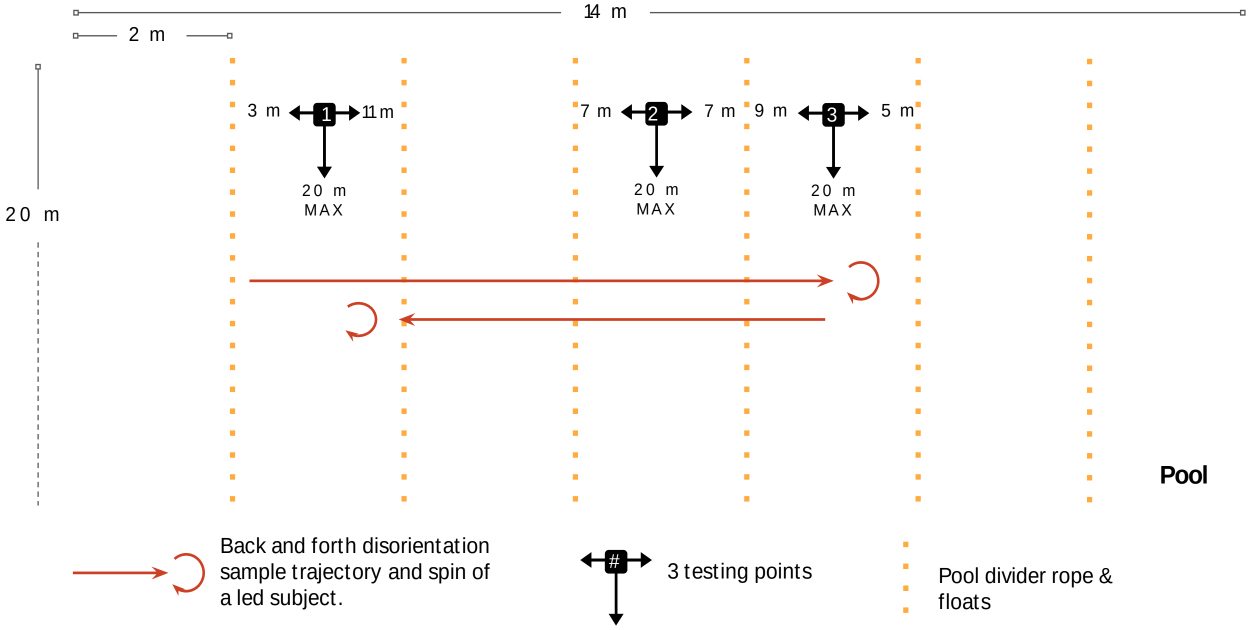


Figure 26: Pool Distance Experiment Set-up Diagram.

responses outside. For this investigation, a new model of the *IrukaTact* module was designed by directly attaching the sonar sensor as part of the thimble. Figure 25 shows this new iteration were the probe looks similar to a flashlight, giving the user directionality feedback based on gauging the boundary distances in the direction they are pointing towards.

There were three pre-selected locations of which three surrounding distances were tested. For each location, there was one tested distance that remained the same which was the maximum length of the pool of 20m, as depicted in Figure 26. The coordinates of each location were: (3m right, 20m center, 11m left), (7m right, 20m center, 7m left), and (9m right, 20m center, 5m left) also shown in figure 16. The motor of the haptic module was set to map the sonar data inversly, the closer the distance, the more pressure that was applied to the fingertip. In this case, the 20m distance was set to 0 pressure, and 1m was set to maximum pressure. Below is the function used to map the ultrasonic range finding data to the *IrukaTact* haptic module output.

$$\text{Output} = \frac{(\text{x} - \text{Smin}) * (\text{Omin} - \text{Omax})}{(\text{Smax} - \text{Smin}) + \text{Omax}}$$

The output is the PWM value of *IrukaTact*, x is the sensor value in the rages or Smin (0) to Smax (1023) which is the analogue sensor input values between 0-5v converted into a digital signal; the input is converted to Omin (0) to Omax (255) which are the ranges of PWM. The output minimum value is mapped to the input's maximum value in order to achieve a stronger haptic sensation if an object or boundary is closer to the subject; the further a target is, the less sensation the participant will feel.

Participants were asked to enter the pool and were helped to place the *IrukaTact Sonar Tip* (Fig. 14) on their finger. They were shown the relationship of the haptic sensation to the distance before beginning the experiment, and shown the controls of shortest and longest distances. They were told the size of the pool which was 20m length by 14m width, and related this information to their initial free-form experimentation.

Figure 27: Pool Distance Experiment Participant and Guide

Once they were acquainted with the mechanism, they were asked to wear swimming goggles that had been painted black inside, inhibiting vision completely (Fig. 27). This allowed them to guide their distance assessment solely via the haptic stimulus. They were turned three times and passed under a few swimming dividing cables in order to disorient them as shown in the experiment set-up diagram in Figure 15. Once they were at the right location, which would have been one of the predetermined distance points, they were instructed to face a specific direction and gauge the distance that they were pointing towards. As they turned to each direction in question they were asked to say how far the boundary of the pool they were pointing towards was from them in meters.

5.2.2.5.3 Results

The results of this experiment can be found in the graph of Figure 28, which shows the statistical results generated by Tukey's multiple comparison test method, which tested the significance of each average result per distance and compared it to one another. These findings show that the performance of the participants was best at discerning the distances when comparing it to the maximum distance of 20 m as shown by the low p-value of <0.01. Participants were also successful in discerning the distances between 3m and 9m, as well as between 3m and 11m.

These results suggest that this echo-haptic translation is successful so long as the participant is able to compare distances, and the further these distances are from one another, the more accurate their responses. It can be determined that participants are able to distinguish between at least three different distance points accurately. However, there is much room for improvement in the design of the device. The ultrasonic range finder was not meant to function underwater and thus there were glitches which sometimes provided an inaccurate distance display to the participant. Also, the pressure display of the *IrukaTact* module can be improved by providing more force, thus able to render more noticeable

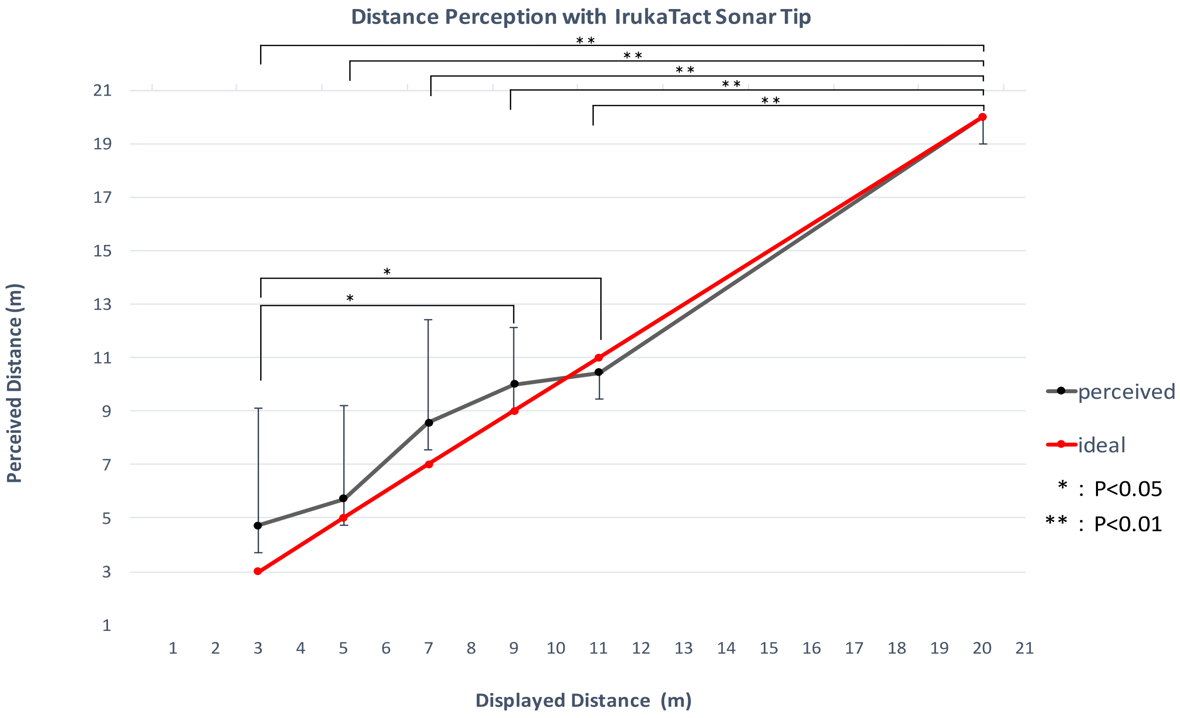


Figure 28: Perceived distance with the *IrukaTact Sonar Tip* average graph with a multiple comparison test data by Tukey's method.

5.2.3 IrukaTact Public Interactions: DemoTanks

IrukaTact has been exhibited world-wide in many public exhibitions[1] under the context of new media art. More specifically, this work is Assistive Device Art, a new form of Device Art that is specifically created as an experiential and exploratory form of assistive technology, seeking to extend human sensory abilities beyond the restoration of normal human ability.

Figure 29: Design Process 3D Printed Tips and Parts

The concept of IrukaTact arose as a new technology able to assist underwater searching, and thus a flooding aid toolkit for locating sunken objects, while treading submerged areas under limited visibility. The exhibition designs that showcase this work usually consisted of two or three *DemoTanks* (Figure 30), the *IrukaTact* glove (Figure 33), cases showing the iterative process of the tip designs such as the *IrukaTact* tip evolution (Figure 29) and display cases that looked like a catalogue of archeological findings including the prototypes of the enclosure of the electronics of the glove, the propeller tips that look like fish fins (Figure 31). Throughout these public demonstrations we collected some comments from participants, about their experience with the *DemoTanks* displaying the associative perception of spatial distance to the haptic intensity variation on the fingertip haptic module.

Figure 30: *DemoTank* annotated image; ‘A’ is the sensor’s range, ‘1’ is the sensor, ‘2’ is the tank, ‘3’ is the haptic module, and ‘4’ is the sensing unit plate.

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[1] This work has been exhibited in:

Post Cities, Ars Electronica, Linz, Austria (2015); Speculum Artium, Trbovlje, Slovenia (2015); Tsukuba Media Arts Festival, Japan (2015); TEI, Eindhoven, Netherlands (2016); G7, Tsukuba, Japan (2016); D-nest Inventors Exhibition, Venice, Italy (2016); IEEE World Haptics, Fürstenfeldbruck, Munich, Germany (2017).

5.2.3.1 DemoTanks: Associative Perception

The fingertip haptic modules were presented in a *DemoTank* unit in order to demonstrate the association of distance to the haptic sensation. These units consist of a sonar sensor stand and a fingertip actuator insert, attached to a water tank (Figure 19). Three of these testing units were designed for large crowds in a festival, each displaying different fingertip actuator models and featuring new ideas for underwater haptic sensations including impeller pumps and propeller models. The two most exhibited actuators were: the *IrukaTact* original tip (Fig.12 and Fig. 18) and the propeller model (Figure 31) both of which display the most contrast in sensation. The sensation of the propeller model is an upward lifting motion mixed with vibration. This actuator works best when the thimble is hovering on the surface of the water. When the propeller is able to mix air and water, there is a significant perceivable haptic stimulation. However, when the propeller model is submerged underwater, the actuation of this type of fingertip haptic module is barely perceivable, many testers were unsure whether they felt any sensation at all. Because of this lack of sensation during full submersion, we wanted to show the difference between a pump actuation model to a propeller actuation model during our demo installations.

Each *DemoTank* has been equipped with a different fingertip haptic module displaying the difference between the propeller (Figure 31) and impeller model. Each model was designed to display varying pressures on the user's finger in relation to the data gathered from the sonar sensor. The strength of the pressure felt by the user was dependent on the proximity of their hand to the sensor; the closer their hand was to the sensor plate, the more pressure they felt on their fingertip.

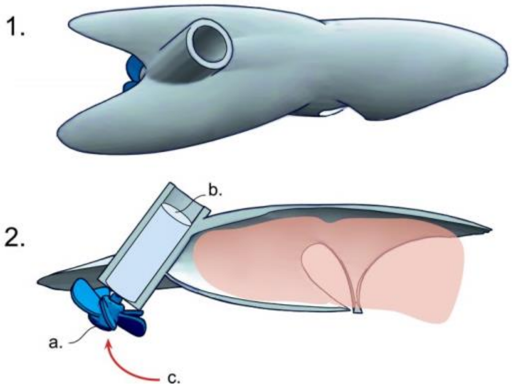

Figure 31: Propeller Haptic Actuator Model

The circuit components for the *DemoTank* units are shown in Figure 30 with numbers associated with each part, a MaxBotix MB7066 sensor (1), a water tank (2), a small motor per haptic fingertip module (3), an electronics enclosure (4) containing: An Arduino Pro Mini, a 12 Volt power supply adaptor, and a PN222 transistor, and an LCD screen. The LCD screen was used to display the distance of the user's hand to the sensor in centimetres and the intensity of the fingertip haptic module's motor.

The *DemoTank's* sonar has a very broad sensing range, from 12cm-10m, which poses a problem for translating the sensed distance into haptic data. The constrains of the ultrasonic range finder are set from its minimum range of 12 cm to the top of the sensing unit plate which is 56 cm, depicted in Figure 30 noted by the arrow labeled (A). For this device, we used the same mapping function as the Distance Assessment experiment, but in this case the analogue sensor reading constraints were modified to reflect the distance in question as aforementioned. Similar to that experiment, activating the sensor closer to the plate initiates the haptic module's maximum speed, and vice versa. During the demonstrations, the participants were guided to use one hand to activate the sensor, and insert a finger from the other hand inside the fingertip haptic module of the tank (Fig. 32). The reason we flipped the direction of the sonar was to simulate the distance of the hand to the ground. This way we could better illustrate the relation between distance to haptic actuation as a parallel sense of touch. We asked participants to imagine they were scanning the ground with their hand and feeling the topography of the ground below.

5.2.3 Observations of Participant Interactions During Demonstrations

These modules have been displayed across various conference and art exhibition settings, and their function has been demonstrated to over a thousand participants from a variety of nationalities, backgrounds and ages. We have gathered comments and observations from these units while in exhibition settings, giving us a wide understanding of how the greater public react to the concept of underwater haptic stimulation. Some of our participants are fellow researchers that understand the concepts of haptic technology, but most of our participants have been curious attendants to Media Art exhibitions. We have had groups of children and groups of elderly tours try *IrukaTact* through the *DemoTanks*.

Figure 32: Participant feeling the distance and haptic actuation correlation on the *DemoTank* unit at the TEI'16 conference exhibition.

Most users have been pleasantly surprised about the haptic sensation that this actuator has provided, sometimes linking it to the water jets of a Jacuzzi. Participants commented 'I get it! I understand the relationship between the distance of my hand to the ground and the sensation on my finger,' and 'This gloves looks really cool, where can I buy one?' This comment about the commercial availability of the product, is directly related to the look and feel of this probe, and the rarity of its function. This feature is an important aspect of Assistive Device Art, where they exist as prototype, artwork, and consumer product, making assistive technology more approachable and replacing disability with desirability. One participant from the D-nest exhibition, who was an archaeological scuba diver suggested that it could be used to locate old coins under the ocean floor, for which case the sensor would have to be replaced with a metal

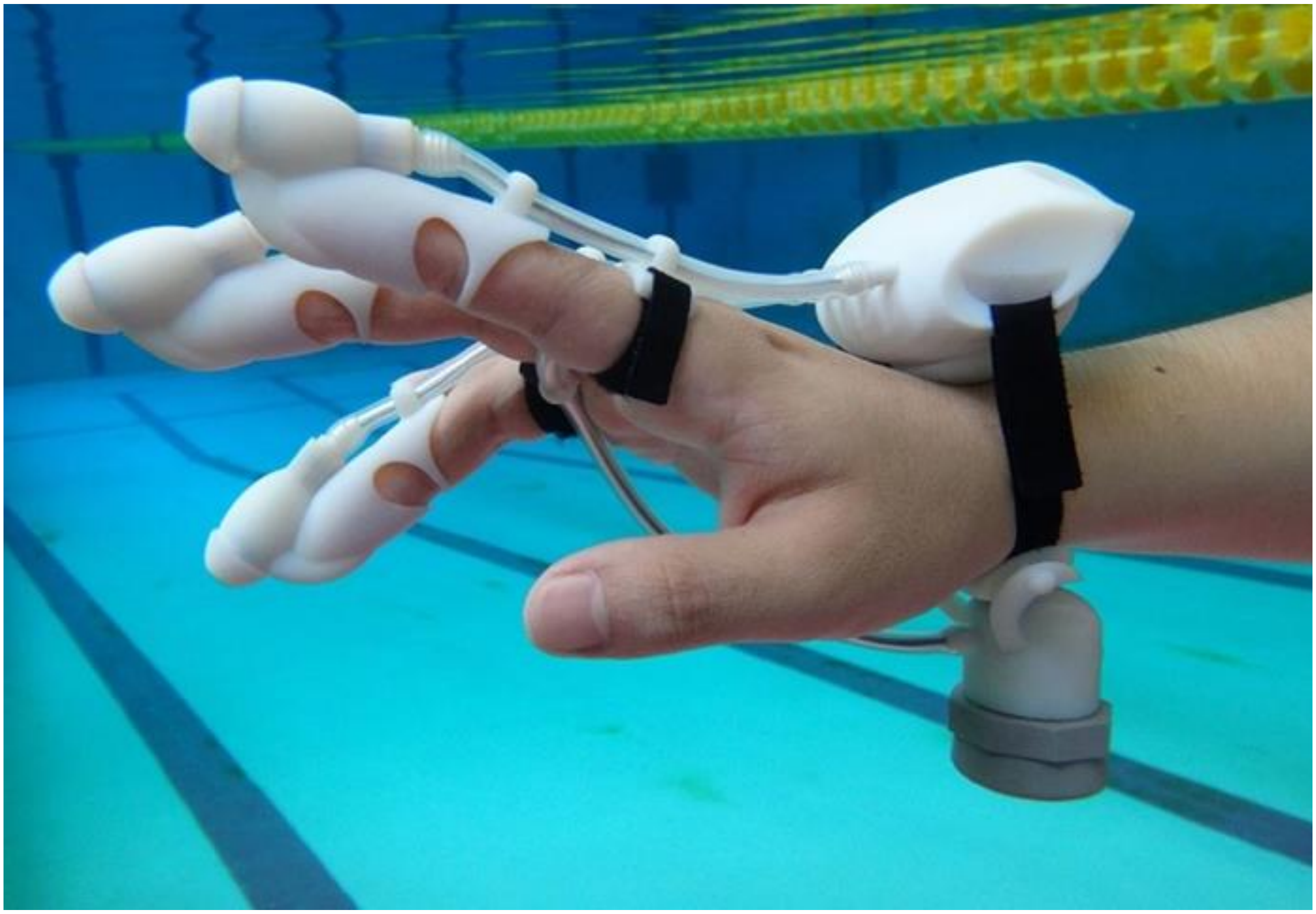

Figure 33: *IrukaTact* underwater haptic search glove.

detector. Most people saw the opportunity of this tool to be extended as an assistive device for blind users, providing an echo-haptic utility that could enrich their scuba diving experience, giving them more information about their surroundings.

5.2.4 Applications

The *IrukaTact* fingertip haptic module is a display tool for underwater applications, which can be paired with a multitude of sensors including the range finding sonar that we used for the *DemoTank*. This haptic technology could also be implemented for virtual reality applications, moving away from probe sensing and instead utilizing gyroscopes and accelerometers to keep track of the user's hand position. This data could be used to superimpose virtual environments where the user can encounter and interact with 3D objects rendered by the varying pressures of the water jets onto the finger pads. While this application is not the primary focus to our research of underwater haptics, it poses a useful extension to the function and application of the underwater haptic actuator module.

5.2.3.1 IrukaTact Glove

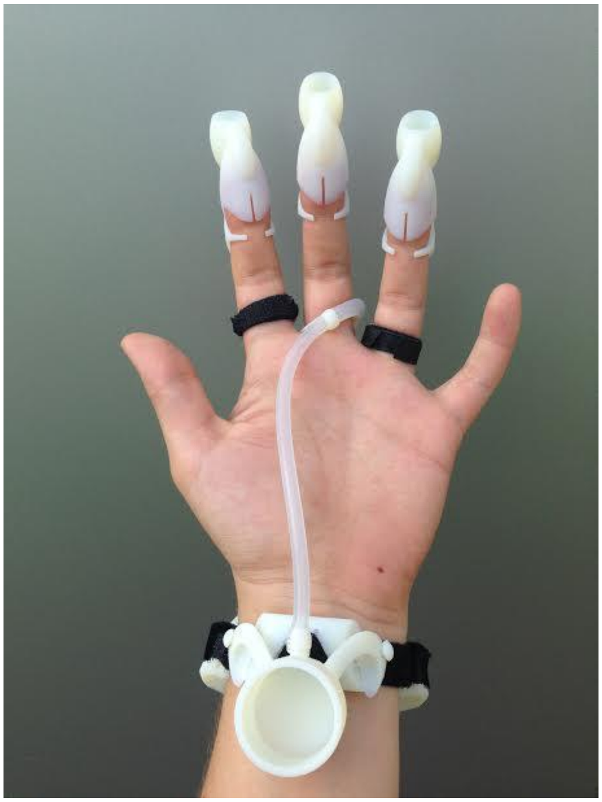

Figure 34: Underside view of the *IrukaTact* Glove

The *IrukaTact* glove (Figure 33) is an Assistive Device Art tool with the capacity of sensory augmentation, given that it provides an extension to the sense of touch in an environment where visibility is hindered. Ideally, people with limited or no visibility can benefit from this device while diving, or to aiding search teams in areas affected by flooding in emergency situations. The files for the glove are open source and anyone can download the DIY and User Manual, where all instructions for assembly and parts list are detailed (Chacin, 2016). The 3D model was created in an online platform which is accessible to anyone through a browser. This kit has been created with the purpose of digital distribution with materials and processes that are readily available in most developed cities, such as Arduino microcontrollers, simple motors, hardware store supplies, and 3D printing. All programming and digital fabrication files can be freely downloaded and adapted, and links to parts available online are provided. The files can be easily edited and remixed by anyone who is interested to contribute to our progress, or deploy the glove for preliminary use. The fingertip haptic modules can be resized for fingers of different sizes, which was a common problem we saw while demonstrating the technology to a wide range of people of all ages and sizes.

5.2.3.2 Interface Design

The look and feel of *IrukaTact* is largely inspired by its name, dolphin, as we designed each part, we were thinking of waves and fins. Our main goal was to design a glove that would allow the user to be able to continue using their hands naturally and feel their environment beyond the tool's feedback. The original *IrukaTact* impeller model (Figures 12 and 18) was used for the glove application because it provides comfort for wearability, while providing sufficient feedback when it's completely submerged underwater. This fingertip haptic module design only inhibits the outermost joint of the finger in order to minimize grasp and movement inhibition.

The *IrukaTact* glove sends mapped signals from the sonar sensor which is attached to the wrist to three fingers, while leaving the thumb and the little finger to be free, minimally covering the hand. Providing the same signal to three fingers allows for the stimulation to be amplified, similar to the

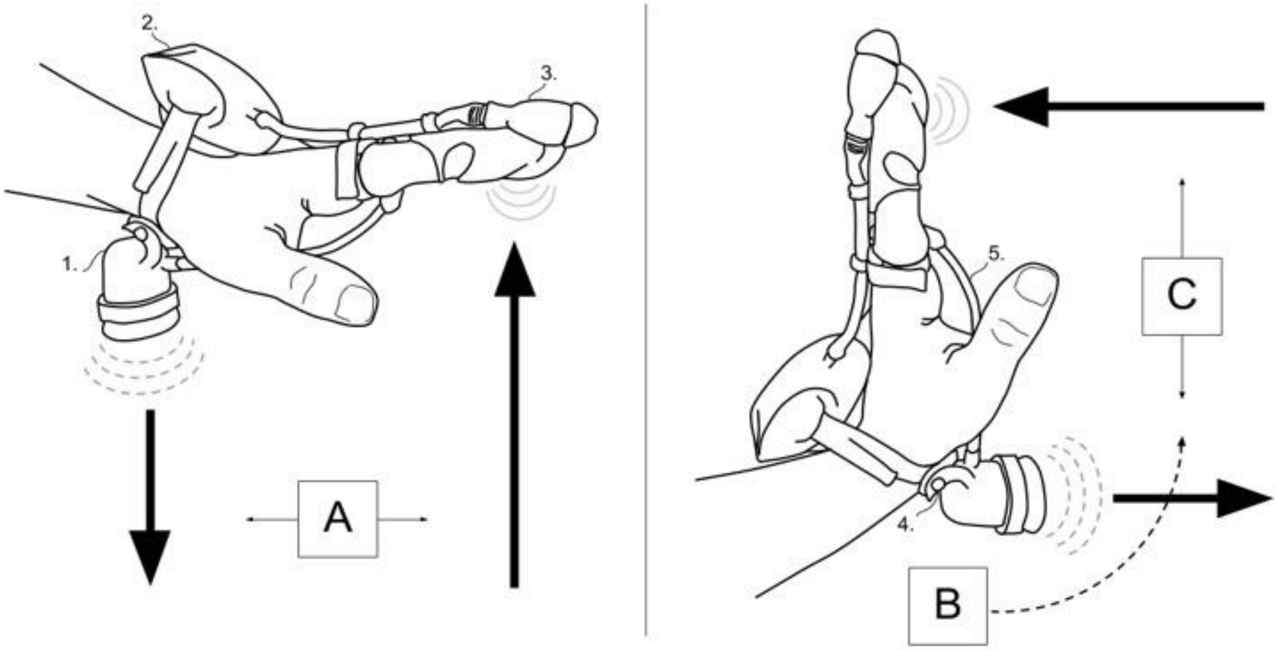

Figure 35: Sensor in Parallel with the Hand Diagram

comment from one of the participants from the haptic resolution experiment. Silicone tubes which house the wires to the finger pumps run along the top of the hand towards the electronics enclosure, which rests on top of the wrist, like a watch or bracelet. The sonar sensor is attached to the bottom of the wrist on a hinge (Figures 33 and 34). The silicone tube that leads the sensor's wires to the enclosure is wrapped around a ring that is worn on the middle finger. The tension of the silicone tube holder on the ring allows for the hinge to move in synchronicity with the user's palm, keeping the sensor in parallel. This way the sensor will pick up the information coming from their palm's direction at all times.

When the user's palm is stretched out without bending the wrist the hinge (Figure 35 #1) is lose, and falls pointing towards the ground. This diagram also shows the relationship (A) between the sensor and the fingertip stimulation, when the user's palm is turned upwards with a wrist movement (B), the face of the sensor points at the same direction (C), thus stimulating the fingers depending on the information detected by the range finder in that direction.

Our device is waterproof, since it was created using a high quality PolyJet 3D printer. As far as sealing the motors we used grease, which is a common practice for waterproofing motors underwater such as pumps and boat propellers. We also designed a twisting cap for the electronics enclosure with a silicone O-ring that would allow the user to open the housing and recharge the device.

5.2.5 *IrukaTact Conclusions*

The *IrukaTact* haptic module presents many other display capabilities beyond the echo-haptic utility of the glove to be expanded for metal detecting purposes or for rendering virtual reality objects and boundaries underwater. Tests suggest that perhaps the force applied by the module could be improved from its maximum of 21,005.8443 N/m^2. Perhaps this could be improved by selecting motors that have a higher torque, or by gearing the motors.

We realized that in order to create a more universal tool, the fingertip actuator housing needs to be more flexible, and not made of a rigid material such as 3D printed plastic. One of the participants noted that 'The tightness of the device and the temperature of the water make a difference in sensation.' The reason for this is that there are many finger sizes, and the reliability of the sensation is dependent on the fitting of the tool. If the fingertip housing is too small, then the user's circulation will be cut, and thus feel less. If the user's finger is entirely too big to fit the thimble housing, they cannot feel the difference of the lower force intensity levels because the water jet cannot reach their finger pad. If the user's finger is too small, then they are unable to reach the channel's disemboguing point, rendering hardly any haptic actuation similar to the previous remark. Furthermore, as an Assistive Device Art tool, the *IrukaTact* glove has gathered positive attention from the public in exhibitions, demonstrations, as well as through the media. This device bridges the gap between desirable and assistive technology, empowering the public's perception on disabilities in a playful way. Assistive technology can go beyond restoring normal human functions and presenting an opportunity to expand the sensory functionality of common devices. In this case study, we found the *IrukaTact Glove* was popular and desirable, even though the utilitarian functionality of the device presents little consumer need alleviation, as it need much technical improvement to reach any level of commodification. Beyond the application of this tool for underwater object searching, an equally important motivation that guided this research was designing new sensations for haptic displays.

6. General Discussion

Transposing an experience goes beyond orchestrating sensory data, it relies on understanding the mechanisms of perception from multiple angles. This research described the intimate relationship that humans have with the computing devices and argue that all technology is assistive. The eager adoption of the smartphone and our shift towards strong dependability on this device has made it become a kind of cognitive prosthetic. Mobile, wearable devices arise from the closely entangled history of the body potentials and the beginning of the battery. We consider the physical characteristics of these devices and propose that through the integration of AT and the miniaturization of their scale, they will become more integrated with our physiology. While the enhancement of visual displays has been dependably advancing, there has been little improvement in alternative-modality digital displays. Audio displays have also received important attention, and while there are incredible advancements for the realism that these devices render, users will always seek an ever more authentic digital experience. This experience is multimodal and integrative, and can be crafted by training apparatuses using sensory substitution methods. Haptic displays have been slowly incorporated in consumer electronics in its most basic function, the vibrating motor. While there are specific haptic display devices, these are usually application specific. An area that has seen the most state-of-the-art haptic displays is surgical laparoscopic displays. These are cumbersome, large devices, similar to the bulky quality of the first computers. As we saw in the trajectory for screen based mobile device incorporation, haptic displays will also become further integrated into our prosthetic toolkit. Mechanoreception is the basis of tactile experience, paired with sound, this perceptual capacity allows us to gain information from the vibrations of our surrounding.

The tangibility of digital information is the next frontier for crafting and manipulating our own experience. Here we also posed questions about the lengths at which humans are willing to integrate new abilities into their physiological architectures, while these enhancements may hinder some of their normal abilities. While there is a small following to the Cyborg Art movement and other sub-culture groups such as Grinders, DIY performers of surgical body modification, non-invasive means for human-computer integration and body augmentation are preferred and more likely to be adopted. Beyond the utility of bodily enhancement, we proposed that most people are interested in learning more about their physiology, and while the skills gained through ADA may not be applicable for utilitarian purposes, the mere curiosity to experience a new perspective is enticing enough for people to engage with AT.

Expanding the experiences of digital displays has been the impetus of ADA as it frames and observes the impulse towards our evolutionary future. This research proposes that HCI borrow from the study of cognitive or motor disabilities, as a way for observing new frontiers for human perceptual and motor adaptation. We reviewed the mechanisms of perception from a neuroscientific perspective, where a new approach for studying sensory experience as a multimodal process is emerging. While the gestalt approach to the study of cognition is relatively new, the compartmentalization of the mind in separate modalities is becoming a concept of the past. The research we have analyzed suggests that the mind is a multimodal organ, and that while there are areas that process specific raw information, perception is an aggregation of a multitude of information. This multimodality also supports the theories of neuroplasticity, allowing the processing power of the brain to be distributed to the modalities available to a specific physiological architecture. This explains why blind individuals may have a heightened sense of hearing in comparison with visually abled people. We considered the visuospatial abilities of various perceptual architectures such as the cases of blind imagination, where the physiological phenomena of visual perception are intact, but the imagery has lost its visual qualities. Or for example, in the case of visual cortex activation in braille reading blind individuals while performing discriminatory tasks. We learned that blind individuals have preference an egocentric perception to space, while sighted subjects have an allocentric preference. From all of these insights we proposed that devices that pose a new visuospatial framework can facilitate the enhancement of trans-modal awareness. The perception of experience is the interpretation of our senses in a spatiotemporal transformative interplay that aggregates information from multiple sources of input.

7. Conclusion

This thesis described the concept of ADA, as brought forth by the author, and its origins by observing the phenomena that surround the aesthetics of prosthesis-related art. ADA was presented as a framework by which to classify, design, and evaluate technology within the cross-section of AT and Art. This concept described a method by which to innovate on digital display technology while deeply investigating the structures of empirical contemplation and facilitating a way of reflecting on our perception through physical and sensory extensions. ADA is a platform for interactive transformation that is the sensorimotor dance of body and environment. AT addresses the necessity of a shared experience, where all bodies have the capability in engaging in the same everyday tasks. In contrast, ADA takes inspiration from atypical physiologies with the aim of creating perceptual models that provide a new shared experience from a multimodal mediated perspective. Assistive Device Art investigates the limits of a mediated embodiment by reframing the user base AT and making it desirable to a broader public. It presents an avenue for exploring new sensory perspectives and contemplating on the transient nature of our condition as human bodies and our relationship to technology. This art reimagines our future bodies proposing new avenues of HCI integration, often camouflaging itself as a consumer product indulging the illusion of escaping our experiential reality. It measures the public's willingness to engage with Assistive Technology and to further human–computer integration while they seek to enhance their experience.

ADA design is an interdisciplinary undertaking where the theoretical models of engineering, psychophysics, design, and philosophy entangle. This researched proposed a framework by which to integrate HCI, sensory and perception science, and Art, by borrowing from some of the methodologies that pertain to these fields. Through employing this framework this research yielded two new interfaces, *Echolocation Headphones* and *IrukaTact Glove*. Furthermore, we described the design process, psychophysical evaluation, and future applications of the *Echolocation Headphones* and the *IrukaTact* haptic module and its various iterations, relating their provenience as ADA tools. Through these interfaces we tested the feasibility of AT methods for abled individuals as a mode of investigating the perceptual ability for visuospatial multimodal integration. As for the *Echolocation Headphones,* this interface provided most subjects with a positive experience. They were able to distinguish between distances of objects, as well as to navigate their surrounding while on average finding an open pathway. Moreover, this interface exhibited as an artwork provoked attention and willingness from participant interaction. There were some aesthetic considerations about the quality of sound that these devices used for the echolocation task, where the white noise was "jarring", but the most effective. In the case of *IrukaTact,* echo-haptic location underwater presented more challenges. A new haptic display mechanism was devised in order to actuate the fingertips underwater while retaining agency of their hands mobile functions. This new underwater haptic actuator module was then paired with a range-finding probe, and translated the distance detected to water pressure. While the design of this haptic actuator is an engineering contribution, the *IrukaTact Glove* is an ADA tool. This prototype also received public attention through the 'viralization' phenomena previously described in the methodology of this research. Albeit, the utilitarian aspects of this technology are questionable, these interfaces provide more than an engineering solution. They are physically proposed questions that ask "How would you like to be physiologically enhanced?" ADA borrows from AT and artistically crafts new sensory performances that inquire and propose new perceptual models towards a future of more integrated human-computer systems that are passive and augmentative co-evolving and co-adapting.

Acknowledgements

The research conducted for this manuscript and prototype were supported by the Empowerment Informatics department at the University of Tsukuba, University of California, Los Angeles, and in small part by the National Science Foundation. This research has been made possible by the careful consideration and advisement of Pr. Hiroo Iwata, Pr. Victoria Vesna, and Pr. Hiroaki Yano, and with the editing help of Tyson Urich and Nicholas Spencer. I would also like to extend my gratitude to Takeshi Oozu, who assisted me in many occasions and collaborated with me on the *IrukaTact* project.

References

A. M., Et al. (1992). *U.S. Patent No. EP 0688125 A1*. Washington, DC: U.S. Patent and Trademark Office.

Anders Björkman, Niels Thomsen and Lars Dahlin (2011). New Treatment Strategies in Diabetic Neuropathy, Recent Advances in the Pathogenesis, Prevention and Management of Type 2 Diabetes and its Complications, Mark B. Zimering, MD, PhD (Ed.), ISBN: 978-953-307-597-6

Antonellis A (ed) (2013) Net art implant. http://www.anthonyant onellis.com/news-post/item/670-net-art-implant. Accessed 12 Sept 2017

Anthony, Sebastian (2012) GoFlow: a DIY tDCS brain-boosting kit. In: ExtremeTech. https://www.extremetech.com/extreme/121861-goflow-a-diy-tdcs-brain-boosting-kit. Retrieved December 23, 2017

Ardila A, Bernal B, Rosselli M (2016) How Extended Is Wernicke's Area? Meta-Analytic Connectivity Study of BA20 and Integrative Proposal. Neuroscience Journal 2016:1–6. doi: 10.1155/2016/4962562

Au Whitlow WL (1997) Echolocation in dolphins with a dolphin–bat comparison. Bioacoustics 8:137–162. doi:10.1080/09524622. 1997.9753357

Auger J, Loizeau J (2002) Audio tooth implant. In: http://www.auger-loizeau.com/projects/toothimplant.Accessed 12 Aug 2017

Bach-y-Rita, P. (1972). Brain mechanisms in sensory substitution. New York: Academic Press.

Bach-y-Rita P, Kaczmarek KA, Tyler ME, Garcia-Lara J (1998) Form perception with a 49-point electrotactile stimulus array on the tongue. J Rehabilit Res Dev 35:427–430

Bach-y-Rita, Paul, and Stephen W. Kercel. 2003. "Sensory substitution and the human–machine interface." *Trends in Cognitive Sciences* 7, no. 12, 541-546. doi:10.1016/j.tics.2003.10.013.

Bau, O.; Poupyrev, I.; Israr, A.; Harrison, C. (2010) TeslaTouch. In Proceedings of UIST '10, pages 283–292.

Bedny, Marina (2011) Interview In:"Parts of brain can switch functions" - MIT News Office. 17 Dec. 2012

Beta Tank, Eyal B, Michele G (2007) Eye candy. In: Eyal B (ed) Studio. http://www.eyalburstein.com/eye-candy/1n5r92f24hltmysrkuxtiuepd6nokx. Accessed 12 Aug 2017

Blakemore S-J, Frith U (2005) The learning brain: lessons for education. Blackwell Publishing, Malden. ISBN 1-4051-2401-6

Brain Center America (2008) Brain functions: visuospatial skills. http://www.braincenteramerica.com/visuospa.php. Accessed May 2013

Brain, R. (1954). Loss of Visualization. *Proceedings of the Royal Society of Medicine*, *47*(4), 288–290.

BrainPort V100 Vision Aid. (n.d.). Wicab. Retrieved December 1, 2017, from https://www.wicab.com/

Cassinelli, Alvaro, Carson Reynolds, and Masatoshi Ishikawa (2006) "Augmenting spatial awareness with haptic radar." Wearable Computers, 2006 10th IEEE International Symposium on. IEEE.

Cattaneo, Z., Vecchi, T., 2011, *Blind vision. The neuroscience of visual impairment*. Massachusetts: The MIT Press.

Chacin, Aisen C. (2015) *IrukaTact*. 24 Oct. 2015 <http://www.aisencaro.com/iruka.html>

Chacin AC (2013) Sensory pathways for the plastic mind. http://aisencaro.com/thesis2.html. Accessed 25 May 2017

Collignon O, Voss P, Lassonde M, Lepore F (2008) Cross-modal plasticity for the spatial processing of sounds in visually deprived subjects. Exp Brain Res 192:343–358. doi:10.1007/ s00221-008-1553-z D3A Lab at Princeton University (2010) http://www.princeton.edu/3D3A. Accessed 20 May 2013

Degenaar, Marjolein and Lokhorst, Gert-Jan (2005) "Molyneux's Problem", *The Stanford Encyclopedia of Philosophy.*Winter 2017 Edition., Edward N. Zalta (ed.), URL = <https://plato.stanford.edu/archives/win2017/entries/molyneux-problem/>.

"Dexta Robotics." (2014) 24 Oct. 2015 <http://www.dextarobotics.com/>

Dinkla S (1996) From interaction to participation: toward the origins of interactive art. In: Hershman-Leeson (ed) Clicking in: hot links to a digital culture. Bay, Seattle, p 279–290

D. M. (2017, December 12). *Psychophysical Isomorphism*. Lecture presented at 2009 Cognitive Neuroscience Annual Spring Retreat and Kavli Institute for Brain and Mind Symposium. in Http://www.psychologyconcepts.com/psychophysical-isomorphism-don-macleod-may-2-2009/.

Driver, Jon, and Charles Spence. 2000. "Multisensory Perception: Beyond Modularity and Convergence." *Current Biology* 10 (20): R731-R735.doi:10.1016/s0960 9822(00)00740-5.

Dunne A, Raby F (2014) Speculative everything: design, fiction, and social dreaming. MIT Press, Cambridge. ISBN: 9780262019842

Encyclopædia Britannica. (2017). Gestalt Psychology. Retrieved December 2, 2017, from: https://www.britannica.com/science/Gestalt-psychology

Evreinova, T.V.; Evreinov, G.; Raisamo, R. (2012) Haptic visualization of bathymetric data. Haptics Symposium (HAPTICS), IEEE. 359-364.

Foc.us "Go Flow 1020 - TDCS Stimulator, Battery, Cable, Electrodes, Sponges & 1020 Hat." Foc.us TDCS Bran Stimulators with EEG, www.foc.us/go-flow-pro-1020. Retrieved December 1, 2017.

Freud, Sigmund. 1961. *Standard Edition of the Complete Psychological Works of Sigmund Freud, Volume XXI (1927-1931): The Future of an Illusion, Civilization and Its Discontents, and Other Works*. London: Hogarth Press and the Institute of Psycho-Analysis.

Glezerman TB, Balkoski VI (2002) Parietal-Occipital Region: Spatial Perception and Word Form. In: Language, Thought, and the Brain. Cognition and Language: A Series in Psycholinguistics. Springer, Boston, MA DOI: https://doi.org/10.1007/0-306-47165-5_4

"GoFlow - World's First tDCS Kit." 2012. 17 May. 2013

[1]Gonzalo Fonrodona, Isabel and Gonzalo Rodríguez-Leal, Justo (2015) *The pioneering research of Justo Gonzalo (1910–1986) on brain dynamics.* In: http://hdl.handle.net/10347/4341 Accessed: December 2, 2017

Goodale MA, Milner A (1992) Separate visual pathways for perception and action. Trends Neurosci 15:20–25. doi:10.1016/0166-2236(92)90344-8

Guillot P (2016) Pad Library. In: Patch storage. http://patchstorage. com/pad-library/. Accessed 10 May 2017

Haberkern R (2012) How directional speakers work. Soundlazer. http://www.soundlazer.com/. Accessed 26 May 2017

Hagen, Susan, 2012. The Mind's Eye. Rochester Review. Vol. 74, No. 4.

Holosonics Research Labs (1997) About the inventor: Dr Joseph Pompei. In: Audio spotlight by Holosonics. https://www. holosonics.com/about-us-1/. Accessed 26 May 2017

Holzner D (2008) The envelope generator. In: Hyde, Adam (ed 2009) Pure data. https://booki.flossmanuals.net/pure-data/audio-tutorials/envelope-generator. Accessed 26 May 2017

Hoshi, Takayuki, et al. (2010) Noncontact tactile display based on radiation pressure of airborne ultrasound. Haptics, IEEE Transactions on 3.3, 155-165

Hoshino, Keisuke, et al. (2015) "Jorro Beat: Shower Tactile Stimulation Device in the Bathroom." Proceedings of the 33rd Annual

ACM Conference Extended Abstracts on Human Factors in Computing Systems. ACM.

Houde S, Hill C (1997) What do prototypes prototype? Handbook Human Computer Interact. doi:10.1016/b978-044481862-1.50082-0

Houston, Edwin James (1905) "Electricity in Everyday Life", Chapter XXII. P. F. Collier & Son.

Hutto D, Myin E (2013) A helping hand. Radicalizing enactivism: minds without content. MIT Press, Cambridge. 46. ISBN 9780262018548

Ihde D (1979) Tecnics and praxis, vol 24. D. Reidel, Dordrecht, pp 3–15. doi:10.1007/978-94-009-9900-8_1

Iwasaki M, Inomara H (1986) Relation between superficial capillaries and foveal structures in the human retina. Investig Ophthalmol Vis Sci 27:1698–1705. http://iovs.arvojournals.org/article.aspx?articleid=2177383.

Iwata H (2000) Floating eye. http://www.iamas.ac.jp/interaction/i01/works/E/hiroo.html. Accessed 25 May 2017

Iwata H (2004) What is Device Art. http://www.deviceart.org/. Accessed 10 April 2017

Iwata, Hiroo (2008) "History of haptic interface." *Human haptic perception: Basics and applications* 355-361.

Kaas, Jon H. (1991)"Plasticity of sensory and motor maps in adult mammals."Annual review of neuroscience 14.1:137-167.

Ken'ichi Koyanagi, Yuki Fujii, and Junji Furusho. 2005. Development of VR-STEF system with force display glove system. In Proceedings of the 2005 international conference on Augmented Tele- existece (ICAT '05). ACM, New York, NY, USA, 91-97.

Kish D (2011) Blind vision. In: PopTech: PopCast http://poptech.org/popcasts/daniel_kish_blind_vision. Accessed 20 May 2013

Kreidler J (2009) 3.3 Subtractive synthesis. In: Programming electronic music in Pd. http://www.pd-tutorial.com/english/ch03s03.html. Accessed 3 Mar 2017

Kusahara M (2010) Wearing media: technology, popular culture, and art in Japanese daily life. In: Niskanen, E (ed) Imaginary Japan: Japanese fantasy in contemporary popular culture. Turku: International Institute for Popular Culture. http://iipc.utu.fi/ publications.html. Accessed 25 May 2017

LAO (Laboratory for Applied Ontology). 2017. "Relation Schematic-Relation in Theory Structuring-Concepts." Ontolingua Reference Manual. Accessed February 10 2017. http://www.loa.istc.cnr.it/old/medicine/structuring-concepts/relation66.html.

Lundborg G, Rose´n B, Lindberg S (1999) Hearing as substitution for sensation: a new principle for artificial sensibility. J Hand Surg 24(2):219–224

Merabet LB, Amedi A, Pascual-Leone A (2006) Activation of the visual cortex by Braille reading in blind subjects. Reprogramming the Cerebral Cortex 377–394. doi:10.1093/acprof:oso/9780198528999.003.0022

Mishkin M, Ungerleider LG (1982) Contribution of striate inputs to the visuospatial functions of parieto-preoccipital cortex in monkeys. Behav Brain Res 6:57–77. doi:10.1016/0166- 4328(82)90081-x

Nakamura, Taira, et al. (2014) "Localization Ability and Polarity Effect of Underwater Electro-Tactile Stimulation." Haptics: Neuroscience, Devices, Modeling, and Applications. Springer Berlin Heidelberg. 216-223.

Nelson, J., McKinley, R. A., Phillips, C., McIntire, L., Goodyear, C., Kreiner, A., & Monforton, L. (2016). The effects of transcranial direct current stimulation (tDCS) on multitasking throughput capacity. *Frontiers in human neuroscience*, *10*.

Nitsche, Michael A et al. "Facilitation of implicit motor learning by weak transcranial direct current stimulation of the primary motor cortex in the human." Journal of Cognitive Neuroscience 15.4 (2003): 619-626.

Noordzij, M.L., Zuidhoek, S., Postma, A., 2006, The influence of visual experience on the ability to form spatial mental models based on route and survey descriptions. *Cognition*, 100, 321- 342.

Ostrovsky Y, Andalman A, Sinha P (2006) Vision Following Extended Congenital Blindness. Psychological Science 17:1009–1014. doi: 10.1111/j.1467-9280.2006.01827.x

Pascual-Leone, Alvaro et al. (2011) "Characterizing brain cortical plasticity and network dynamics across the age-span in health and disease with TMS-EEG and TMS-fMRI." Brain topography 24.3: 302-315.

Pasqualotto, A., Proulx, M.J., 2012, The role of visual experience for the neural basis of spatial cognition. *Neuroscience and Biobehavioral Reviews*, 36, 1179-1187.

Pasqualotto, A., Spiller, M.J., Jansari, A.S., Proulx, M.J., 2013, Visual experience facilitates allocentric spatial representation.

Picard DJ, Hulse J, Krajewski J (2009) Integrated fire exit alert system. US Patent 7528700. 5 May 2009

Pfeiffer, Max; Schneegass, Stefan; Alt, Florian; Rohs, Michael (2014) Let me grab this: a comparison of EMS and vibration for haptic feedback in free-hand interaction. In Proceedings of the 5th Augmented Human International Conference (AH '14). ACM, New York, NY, USA, Article 48, 8 pages.

Pullin G (2009) Desing meets disability. Massachusetts Institute of Technology Press, Massachussetts

Richter, Hendrik; Manke, Felix; Seror, Moriel (2013) LiquiTouch: liquid as a medium for versatile tactile feedback on touch surfaces. In Proceedings of the 7th International Conference on Tangible, Embedded and Embodied Interaction (TEI '13). ACM, New York, NY, USA, 315-318.

Rosch E, Thompson E, Varela FJ (1991) The embodied mind: cognitive science and human experience. MIT Press, Cambridge, MA

Sacks O. (2007) Musicophilia: tales of music and the brain. Knopf Publishing Group; New York, NY. pp. 314–315.

Sadato N, Pascual-Leone A, Grafman J, et al (1996) Activation of the primary visual cortex by Braille reading in blind subjects. Nature

380:526–528. doi: 10.1038/380526a0

Sanes, Jerome N, and John P Donoghue (2000) "Plasticity and primary motor cortex." Annual review of 81 neuroscience 23.1: 393-415.

Schwartzman M (2011) See yourself sensing: redefining human perception. Black Dog Publishing, London, pp 98–99. ISBN: 9781907317293

ScorpionZZZ's Lab (2013) SGenerator (Signal Generator). http:// sgenerator.scorpionzzz.com/en/index.html. Accessed 11 May 2017

Snyder A. Explaining and inducing savant skills: privileged access to lower level, less-processed information. *Philosophical Transactions of the Royal Society B: Biological Sciences*. 2009;364(1522):1399-1405. doi:10.1098/rstb.2008.0290.

Stearns, Paul. 2014. "Introduction to Kant's Critique of Pure Reason: Part 4." *YouTube*. https://youtu.be/UPJh6fRpDjc?list=PLFGHE1xQFhhzLba8GxgYtjAD6cfKoQJmH.

Stein, B., Meredith, M. A., & Wallace, M. T. (1993). The visually responsive neuron and beyond multisensory integration in cat and monkey. In *The Visually Responsive Neuron: From Basic Neurophysiology to Behavior* (Vol. 96). Amsterdam, The Netherlands: Elseiver.

Stein BE, Stanford TR, Rowland BA (2009) The neural basis of multisensory integration in the midbrain: Its organization and maturation. Hearing Research 258:4–15. doi: 10.1016/j.heares.2009.03.012

[1]Stein BE (2012) The new handbook of multisensory processes. The MIT Press.

Sterlac (1980) Third hand. http://stelarc.org/?catID=20265. Accessed 25 May 2017

Suzuki, Y.; Minoru, K. (2005) Air jet driven force feedback in virtual reality. IEEE Computer Graphics and Applications, 25(1): 44-47, 2005.

Szubielska M (2014) Strategies For Constructing Spatial Representations Used By Blind And Sighted Subjects. Studia Psychologica 56:273–285. doi: 10.21909/sp.2014.04.666

Temple, Stephen. 2017. Vintage Mobiles. GSM History: History of GSM, Mobile Networks, Vintage Mobiles Retrieved December 20, 2017, from http://www.gsmhistory.com/vintage-mobiles/#orbitel_901_1992

Thaler L, Castillo-Serrano J (2016) People's ability to detect objects using click-based echolocation: a direct comparison between mouth-clicks and clicks made by a loudspeaker. PLoS ONE. doi: 10.1371/journal.pone.0154868

Thompson E (2010) Chapter 1: The enactive approach. Mind in life: biology, phenomenology, and the sciences of mind. Harvard University Press, Cambridge. ISBN 978-0674057517

Treffert D.A. (2005) The savant syndrome in autistic disorder. In: Casanova M.F., editor. Recent developments in autism research.Nova Science Publishers, Inc.; New York, NY. pp. 27–55.

Treffert, Darold A. (2009) "The savant syndrome: an extraordinary condition. A synopsis: past, present, future." Philosophical

Transactions of the Royal Society B: Biological Sciences 364.1522:1351-1357.

TriState (2014) Supplement for frequency modulation(FM) In: TriState. http://www.tristate.ne.jp/parame-2.htm. Accessed 26 May 2017

TriState (2014) World’s first parametric speaker experiment Kit. In: TriState g. http://www.tristate.ne.jp/parame.htm. Accessed 26 May 2017

UW Dept. Biomedical Engineering. (2006). Founder. Retrieved December 11, 2017, from https://tcnl.bme.wisc.edu/laboratory/founder

WAFB (2010) Daniel Kish, Our President. In: World access for the blind. http://www.worldaccessfortheblind.org/node/105. Acces- sed 20 May 2013

Warwick K (2002) In: Kevin Warwick Biography. http://www. kevinwarwick.com/. Accessed 25 Sept 2017

Wood M (2010) Introduction to 3D audio with professor choueiri. Video format. Princeton University. https://www.princeton.edu/3D3A/. Accessed 10 May 2013

Yoshimoto, S.; Hamada, Y.; Tokui, T.; Suetake, T.; Imura, M.; Kuroda, Y.; Oshiro, O. (2010) Haptic canvas: dilatant fluid based haptic interaction. In proceedings of ACM SIGGRAPH 2010 Emerging Technologies. ACM, New York, NY, USA, 49-52.

Zeman AZ, Sala SD, Torrens LA, et al (2010) Loss of imagery phenomenology with intact visuo-spatial task performance: A case of ‘blind imagination.’ Neuropsychologia 48:145–155. doi: 10.1016/j.neuropsychologia.2009.08.024

Bibliography

Arias, Claudia, and Oscar A. Ramos. “Psychoacoustic Tests for the Study of Human Echolocation Ability.” *Applied Acoustics*, vol. 51, no. 4, 1997, pp. 399–419., doi:10.1016/s0003-682x(97)00010-8.

Brucker-Cohen, Jonah. “Alerting Infrastructure!” *Proceedings of the 2016 CHI Conference Extended Abstracts on Human Factors in Computing Systems - CHI EA '16*, 2016, doi:10.1145/2851581.2891082.

Chen, Gang, et al. “An Adaptive Non-Parametric Short-Time Fourier Transform: Application to Echolocation.” *Applied Acoustics*, vol. 87, 2015, pp. 131–141., doi:10.1016/j.apacoust.2014.06.018.

Fründt, Hans. “Echolocation: The Prelinguistic Acoustical System.” *Semiotica*, vol. 125, no. 1-3, 1999, doi:10.1515/semi.1999.125.1-3.83.

Gray, Carole, et al. *Developing a Research Procedures Programme for Artists & Designers*. Centre for Research in Art & Design, Robert Gordon University, 1995.

Gray, Carole, and Julian Malins. *Visualizing Research: a Guide to the Research Process in Art and Design*. Ashgate, 2012.

Haraway, Donna J. “A Cyborg Manifesto.” *Manifestly Haraway*, Jan. 2016, pp. 3–90., doi:10.5749/minnesota/9780816650477.003.0001.

Haraway, Donna J. “The Virtual Speculum in the New World Order.” *Feminist Review*, vol. 55, no. 1, 1997, pp. 22–72., doi:10.1057/fr.1997.3.

Hatzfeld, Christian, and Thorsten A. Kern. *Engineering Haptic Devices: a Beginner's Guide*. Springer London, 2014.

Kozhevnikov, Maria, and Mary Hegarty. “A Dissociation between Object Manipulation Spatial Ability and Spatial Orientation Ability.” *Memory & Cognition*, vol. 29, no. 5, 2001, pp. 745–756., doi:10.3758/bf03200477.

Lowery, Percival Chelston. *Art and Esthetics as Applied to Prosthetics*. White Dental Manufacturing Co., 1921.

Mann, Steve. “Decon2 (Decon Squared): Deconstructing Decontamination.” *Leonardo*, vol. 36, no. 4, 2003, pp. 285–290., doi:10.1162/002409403322258691.

“Media and Prosthesis: The Vocoder, the Artificial Larynx, and the History of Signal Processing.” *Qui Parle*, vol. 21, no. 1, 2012, pp. 107–149., doi:10.5250/quiparle.21.1.0107.

Moore, Brian C. J., et al. *Basic Aspects of Hearing Physiology and Perception*. Springer, 2013.

Papadopoulos, Timos, et al. “Identification of Auditory Cues Utilized in Human Echolocation - Objective Measurement Results.” *2009 9th International Conference on Information Technology and Applications in Biomedicine*, 2009, doi:10.1109/itab.2009.5394427.

Pinder, Shane D., and T. Claire Davies. “Exploring Direct Downconversion of Ultrasound for Human Echolocation.” *Proceedings of the 8th ACM SIGCHI New Zealand Chapter's International Conference on Computer-Human Interaction Design Centered HCI - CHINZ '07*, 2007, doi:10.1145/1278960.1278967.

Poissant, Louise. “New Media Dictionary.” *Leonardo*, vol. 36, no. 3, 2003, pp. 233–236., doi:10.1162/002409403321921479.

Rowan, Daniel, et al. “Identification of the Lateral Position of a Virtual Object Based on Echoes by Humans.” *Hearing Research*, vol. 300, 2013, pp. 56–65., doi:10.1016/j.heares.2013.03.005.

Schenkman, Bo N., et al. “Human Echolocation: Acoustic Gaze for Burst Trains and Continuous Noise.” *Applied Acoustics*, vol. 106, 2016, pp. 77–86., doi:10.1016/j.apacoust.2015.12.008.

Seago, Alex, and Anthony Dunne. “New Methodologies in Art and Design Research: The Object as Discourse.” *Design Issues*, vol. 15, no. 2, 1999, p. 11., doi:10.2307/1511838.

Simner, Julia. “Defining Synaesthesia.” *British Journal of Psychology*, vol. 103, no. 1, Nov. 2011, pp. 1–15., doi:10.1348/000712610x528305.

Stetson, Chess, et al. “Motor-Sensory Recalibration Leads to an Illusory Reversal of Action and Sensation.” *Neuron*, vol. 51, no. 5, 2006, pp. 651–659., doi:10.1016/j.neuron.2006.08.006.

Stiles, William B., and Michael Barkham. “Practice-Based Evidence From the United Kingdom Using the CORE System.” *PsycEXTRA Dataset*, doi:10.1037/e633922012-001.

Tatur, Guillaume. “Scene Representation for Mobility of the Visually Impaired.” *Mobility of Visually Impaired People*, 2017, pp. 283–310., doi:10.1007/978-3-319-54446-5_10.

Thaler, Lore, et al. “Neural Correlates of Natural Human Echolocation in Early and Late Blind Echolocation Experts.” *PLoS ONE*, vol. 6, no. 5, 2011, doi:10.1371/journal.pone.0020162.

Thaler, Lore, and Josefina Castillo-Serrano. “People’s Ability to Detect Objects Using Click-Based Echolocation: A Direct Comparison between Mouth-Clicks and Clicks Made by a Loudspeaker.” *Plos One*, vol. 11, no. 5, Feb. 2016, doi:10.1371/journal.pone.0154868.

Tonelli, Alessia, et al. “Depth Echolocation Learnt by Novice Sighted People.” *Plos One*, vol. 11, no. 6, Mar. 2016, doi:10.1371/journal.pone.0156654.

Tsing, Anna. “Unruly Edges: Mushrooms as Companion Species.” *Environmental Humanities*, vol. 1, no. 1, 2012, pp. 141–154., doi:10.1215/22011919-3610012.

Warwick, Kevin, et al. “Prosthetics: A User Guide for Posthumans.” *The American Journal of Psychology*, vol. 121, no. 1, Jan. 2008, p. 161., doi:10.2307/20445449.

Wickens, Christopher D., et al. *An Introduction to Human Factors Engineering: Pearson New International Edition*. Pearson Prentice Hall, 2014.

Blakeslee, Sandra "BrainPort, Dr. Paul Bach-y-Rita, and Sensory Substitution". *Mind States - Tribe.net*. 23 November 2004. Web. 03 Dec. 2011.<http://mindstates.tribe.net/thread/a8b9f33f-7a6f-4af8-9c0c-588719606271>

"History of the Synapse - Max R. Bennett - Google Books." 2012. 21 May. 2013 <http://books.google.com/books/about/History_of_the_Synapse.html?id=AkdZ07OHassC>

Kendrick, Mandy. "Tasting the Light: Device Lets the Blind "See" with Their Tongues: Scientific American." *Science News, Articles and Information/ Scientific American,* August 13, 2009. Web. 03 Dec. 2011. <http://www.scientificamerican.com/article.cfm?id=device-lets-blind-see-with-tongues>

"Tongue Control Technology." *Think-A-Move, Ltd.* Think-A-Move, Ltd., 2007. Web. 17 Dec. 2011. <http://www.think-a-move.com/tongue.html>.

Wiener, Norbert (1948). Cybernetics, or Communication and Control in the Animal and the Machine. Cambridge: MIT Press. <http://www.pbs.org/transistor/background1/events/radar.html>

Horowitz, Seth S. *The universal sense: how hearing shapes the mind*. Bloomsbury Publishing USA, 2012.

Becker, Robert O, and Gary Selden. *The Body Electric: Electromagnetism and the Foundation of.* NY: Morrow, 1985.

Smith, M., & Morra, J. (2007). *The prosthetic impulse: from a posthuman present to a biocultural future*. Cambridge: MIT Press.

Appendix ii

Guiding Questions:

How can these modes of perception be adopted for popular applications?

Isn’t all technology assistive in a specific capacity of its purpose as a tool?

Can ADA tools enhance people's understanding of what constitutes skill and ability?

Are ADA desirable tools? Can they create an alternative demand for prosthetics?

How necessary is it for the ADA tools to be functional vs. vaporware?

What alternative perceptual methods are useful in computing?

Is there a possible way to achieve non-subtractive super-abilities with non-invasive technology?

Could the ability to further understand spatial information based on sonic proximity be helpful for more than to aid blindness?