Haptic Feedback for Training and Development

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This paper investigates the uses of haptic feedback for training and development purposes through a literature review spanning research and development between 1928 and 2020. The main focuses are on applications of haptic devices and stimuli in promoting attention, education, training, and rehabilitation. This work presents the culmination of Rose Ridder’s Cognitive Science Degree at Swarthmore College under the guidance of Cognitive Science and Psychology Professor Frank Durgin.

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Introduction
The field of haptics is a growing area of research focusing on how touch feedback may be used to improve performance and outcomes. Most commonly associated with virtual reality, haptics has applications in countless other fields that inform user interaction, perception, and skill.

In this examination of existing research on haptic feedback for various applications, I will begin by defining the basis for what is and is not considered haptics. This will include comparisons to other senses and discussion of the use of haptics alongside these senses and in isolation. I primarily investigate the opportunities and uses of haptics in attention, training, education, and rehabilitation. I will examine the fields in which haptics research appears to be lacking and propose ways to investigate haptics usage in these spheres. This includes a discussion of the most appropriate uses of haptic feedback and the circumstances in which it may or may not be most valuable.

Defining Haptics

The Five Senses
There are five primary senses – sight, smell, taste, audition, and touch. Haptics and haptic research focus on the realm of touch and tactile feedback.
From a neuroscience perspective, the cerebrum is responsible for most sensory processing. On a more specific level, within the cerebrum are four lobes – the frontal lobe, occipital lobe, parietal lobe, and temporal lobe – which further divide the processing of incoming information. The parietal lobe unites and interprets signals from the separate senses, but the information from each sense comes from a different place. Visual information primarily comes from the occipital lobe, auditory information comes from the temporal lobe, taste and smell primarily come from the frontal lobe, and the sense of touch comes from the parietal lobe.

These lobes occupy different amounts of space in the cerebrum and on the surface-level cerebral cortex, and they elicit different proportions of neural activity within the brain. By area, the visual systems of the brain accounts for 27% of the cerebral cortex, while auditory regions account for 8%, and proprioceptive and motion regions account for 7% each. Other studies compare neuronal firing rates associated with different senses, with various sources noting that between 30% and 70% of the approximately 3 billion neurons that fire in the brain every second are vision-associated. Of the remaining cerebral activity, it is estimated that 8% is dedicated to touch and 3% to audition.

The sense of touch is primarily represented by any sensations upon the skin – a "skin sensation". There are also examples of tactile experiences extending beyond the skin, such as sensations upon the tongue or deeper within the body. Regardless of the location, these tactile sensations typically fall into categories of depth and stimulation type. The depths of haptic feeling include deep/somatic, surface/superficial, and hyper-mild. The types of stimulation include stationary pressure, smooth motion, vibration, and temperature.

Terminology

Many definitions of haptics exist and understanding the different terms associated with haptics and haptic devices is critical in understanding the potential for this technology. According to the Oxford English Dictionary, the word haptic is defined as, "Of the nature of, involving, or relating to the sense of touch, the perception of position and motion (proprioreception), and other tactile and kinaesthetic sensations." This definition, however, is simultaneously too broad and too narrow for our purposes.

In this work, the term haptics is used to mean the transmission of information using touch and sensory stimulation. Commonly relating to simulation and virtual reality, the emphasis of haptics is on simulated or exaggerated feedback by means of tactile presentation. Haptics may include skin-based tactile stimulation as well as non-skin sensations of touch or pressure in the mouth, anus, genitals, or internal organs.

Haptics are most often thought of in terms of vibrotactile stimulation – vibrations applied to the skin. These vibrations may be used to simulate a variety of sensations, including illusions of an object's presence, position, motion, size, texture, and weight. However, there are numerous ways by which haptic devices provide sensory information, and the combination of types and depths of tactile feedback enable sensing anything from simple touch to complex haptic representations of data and environmental information.

Skin Sensations. The term skin sensation is commonly used in place of the terms tactile and haptic. However, compared to haptics, skin sensations are too general in regard to the characterized sensations, and too limited in being confined only to the skin. Skin sensations include anything perceived upon the skin – temperature, pressure, texture, pain, and more. Skin sensations also extend somewhat beyond the surface layer of the skin – the epidermis – to the dermis and subcutis deeper beneath the surface.

Tactile. Of or relating to touch, tactile stimulation is any sensory information that stimulates the nerves upon the skin or body, creating a sense of physical contact. Likewise, tactile feedback is any form of feedback from incoming data that can be felt upon the body. The term proprioceptive is also sometimes used.

Vibrotactile Stimulation. Vibrotactile stimulation is sensory stimulation using vibration to simulate tactile perception or response and elicit a sense of touch.

Interface. In this examination, an interface is any device or method of connecting two or more others. This intersection may be physical or virtual and communicates information from one entity to another.

Neuroplasticity. The term neuroplasticity relates to the plastic nature of the brain and its neurons and specifically how the brain and its neuronal structure may change and adapt. This can be referred to as "rewiring", "reprogramming", "remapping" and other terms to express the neurological organization and reorganization of information pathways.

Sensory Substitution. Sensory substitution is a method of replacing one sense with another. For example, conveying visual information through feeling, auditory sound through light and other visuals, or any other combination of the five senses. Some scientists and neurobiologists argue that environments are non-sense specific and that, for example, the exact same information that a seeing person perceives can be conveyed to a blind person through one of the other four senses. These arguments posit that the brain can process and substitute sensory information seamlessly across sensory inputs.

Types of Haptics

Terminologies abound regarding the types of haptic information and stimulations that one may perceive. Throughout the literature, terminologies differed despite describing
similar systems, or were identical even while describing divergent technologies. It therefore became especially critical that the scope and terms of this work were well-defined for further investigations and conclusions.

Everyday Examples of Haptics

In defining what haptics is, it is useful to provide a snapshot of uses of both natural and artificial haptics in our everyday lives. Tactile feedback may be expressed in many forms – the pressure of your leg against your chair, the texture of carpet as your feet move across it, or the depression of keys on your keyboard. These are examples of natural haptic interfaces – passive objects eliciting sensory feedback through touch. A more complex example of tactile stimulation comes from our phones and tablets. Haptic feedback is often provided through the vibration of your phone when you touch the virtual home button or play a game with iPhone’saptic processor or Android’s haptic interface [10]. With consumer tablets, reducing space through the deployment of flat touch-keyboards often comes with the addition of haptic feedback to create the illusion of depressing keys as one would do on a traditional 3-dimensional spring-loaded keyboard [11]. Video games also employ the use of haptics and vibration frequently through the use of rumble packs, remotes, and virtual reality simulation to indicate actions and outcomes. For example, Wii Tennis users are alerted to successfully hitting the virtual ball by a momentary vibration of the Wii remote [12].

A body of research exists presenting how haptics may contribute to mobile device usage. From manipulating areas of attention, to typing, to performing actions using a touchscreen, many phone and tablet users consciously and unconsciously interact with haptic feedback mechanisms daily. Many touchscreen and tablet keyboards use haptic technology to provide better feedback to a user upon hitting a key, resulting, at least in tablets, in significant accuracy and speed improvements [11, 13]. On phones, home button presses, multi-screen views, and password patterns rely on haptic technologies frequently. Recent models of iPhones and Androids in the United States have a haptic setting which can be adjusted by the user [14, 15]. Research in this arena suggests users perceive haptics positively when enabled, and that drag-and-drop and path-following tasks benefit significantly from haptic feedback, especially when visual feedback is occluded while executing the task [16, 17]. Research goes as far as to recommend ideal frequencies for haptic feedback and compare the realism of simulated buttons on touchscreens [18, 19]. This research directly impacts millions of users’ interactions with their phones and demonstrates the vast potential of the study of haptics in everyday objects.

Passive, Natural Haptics

Passive haptics are those by which the perceiver must act to receive haptic stimulation. Often, passive haptics may be thought of as perceptions elicited from objects that exist naturally, where a user receives feedback from interacting with that environment, for example, feeling the texture of a surface by running one’s fingers across it.

In this investigation, passive haptics are not the subject of focus. However, principles established through the observation of user interactions with their physical environment can inform inspiration for the types of haptic devices which are our focus. For example, understanding the ways in which people use their fingers to explore objects can inform the development of haptic gloves. In these studies, understanding not only the physics, motion, and abilities of the body, but the feedback to the brain is critical. For fingers specifically, our brains are uniquely prepared to perceive vibration through the fingertips because the ridges and crevices of our fingertips allow specialized touch sensing to observe high-resolution information including textural inconsistencies and gradients [20].

Further observation of behavior may contribute to understanding how a person’s brain recovers after a traumatic injury, like an amputation. Especially in the field of rehabilitation, observing the interaction of users with their natural environments to elicit tactile stimulation can be leveraged in developing technologies to inhibit muscular and neural atrophy, elicit sensory illusions, and regain lost function by conveying haptic information differently or projecting the information to other regions of the body.

Active, Artificial Haptics

Active haptics include devices to exaggerate feedback, create illusions, or convert information. Examples of these include surgical tools to amplify the sense of motion and resistance against body tissues, flat keyboards conveying a sense of key motion when no motion has occurred, and any device that converts one type of sensory information, say vision, into another – specifically, into tactile feedback.

One may think of active haptics as adding or exchanging energy from one form of information to another. In this sense, "active" may be thought of as requiring the input of energy with an output of haptic information. Alongside active haptic devices, the terms artificial, synthetic, and simulation are often used to describe the non-natural aspect of the feedback. In many cases, these terms imply creating perceptions where none should be, or manipulating one type of feedback into another, further conjoining the active and artificial classification of haptics into one.

For this study, we focus on the exaggeration, generation, and conversion of information to synthesize tactile sensation. These artificial, active haptic feedback methods and their im-
implemements and uses provide opportunities for development in many areas of life.

**Haptic Actuation Methods**

Tactile sensations for haptics may be elicited in a variety of ways. With modern technologies, the most common type of haptic feedback is provided using vibrotactile stimulation. This is generally performed with a motor to create physical vibrations that are applied to the skin, which can create illusions of many forms of interaction – motion, weight, pressure, and others. Another common and perhaps easily envisioned haptic interface is through ultrasonic low frequency sound. Sound is already the result of energy moving through space in waves, but most often we name it sound because it is at too high a frequency to feel. However, bass music and other super-low frequencies may be felt. Alternative methods to create the illusion of physical touch include the application of electrical currents, varied temperatures, and even magnetic force manipulation \[9\] \[21\] \[22\] \[23\].

**Research Methods**

Initially, I was interested in haptics in prosthetics. This area is one of emerging interest in the prosthetic industry as it can provide feedback to users who have lost a limb due to amputation. Much focus has been on improved prosthetic functionality, but more recently, providing haptic feedback has gained traction as a way to enable users to sense successful and unsuccessful execution of actions with their prosthetic limb. This was also the subject of my Engineering Culminating Design Exercise which involved developing an electromyogram-controlled prosthetic with vibrotactile haptic feedback \[24\].

However, not wanting to overlap too greatly with that capstone project and interested in the psychology and neurosciences of prosthetic skill acquisition, but simultaneously faced with limitations in the body of prosthetic research, I turned my focus to the neuroscience of limb loss and body representations. A central feature of the body’s representation in the mind is the cortical homunculus, a region of the brain first identified explicitly in 1928 by Wilder Penfield \[25\] \[26\] \[27\]. The subject of many cartoon illustrations, this system in the brain allocates resources to the representation of each part of a person’s body. More resources are devoted to regions that must be more attuned to touch. Most interestingly, if the body changes, as is the case with injury and limb loss, this region reorganizes to devote more resources to the remaining body schema \[28\].

This led to my interest in how the cortical homunculus and other perceptual regions of the brain might be affected by external objects that are used regularly to extend the body’s abilities. These objects could be anything from a highly functional prosthetic, to a blind person’s cane, to a violin bow, to a simple pencil \[29\] \[30\]. From authors who are well known for their studies of tool use, I found interesting work returning to illusions and haptic perception \[6\] \[22\]. These compared how the brain prioritizes visual feedback, but when that feedback is faulty, other senses may take priority. Noting how underutilized haptic stimuli are and how dynamic and subtle they may be while still providing valuable feedback to inform and improve overall environmental perception, I returned to a closer investigation of haptics themselves, including muscular stimulation and feedback mechanisms.

In this topic, which remained my focus, I began by investigating the fields in which haptics are used. These fields include prosthetics, as expected, but are extended and studied in training methods, particularly for very specific tasks such as medical procedures and flight. However, these training methodologies only indicated the use of touch simulation in advanced fields, and I became fascinated with the use of haptics in everyday life that could improve anyone’s skills. Hence, I focused on phone applications and educational tools, with a bit of inquiry into video games as well.

In the sphere of skill training, retraining can be just as important. It parallels well with amputees who must learn to use a prosthetic limb having – in the case of traumatic injuries in adulthood – previously known how to use their biological limb. Now these users must “reprogram” the neural circuits in their brains to use a prosthetic. In the same way, stroke patients or those with balance disorders acquired in adulthood must relearn how to use their bodies and interact with their environments post-injury. This was my focus on rehabilitation, and circled back into the previous research I had pursued with neurolasticity and body representations, using haptics for more seamless integration of feedback mechanisms to inform the body and the brain.

For the research of this thesis, I set a goal of having read and annotated 50 papers on haptics. I initially collected these papers by searching for keywords of "haptics", "mind body extension", "extensions of the body", "tool use", "haptics in surgical skill acquisition", "haptics for education", and "applications of haptic technology" on a variety of platforms including Google, Google Scholar, Swarthmore College Library’s Tripod, and within reputable journals such as IEEE the professional Institute of Electrical and Electronics Engineers, NCBI the National Center for Biotechnology Information, and Research Gate. Initially, I printed numerous articles for a general review of the field, but as I narrowed down my topic area, I began to use the reference lists of particularly informative resources as well as pursue specific information within articles by keyword searches. As the writing of this thesis commenced, my information-gathering and surveying practices were replaced by pointed searches for specific information expanding on topics I had previously read about but for which I did not have enough specific information or documentation to draw informed conclusions.

This research and thesis was also heavily influenced by
three audiobooks I listened to throughout my Junior and Senior years while preparing and completing this text. These were Norman Doidge’s The Brain that Changes Itself [31] and The Brain’s Way of Healing [28], and Sean Kean’s The Tale of the Dueling Neurosurgeons [27]. These books provided discussions of advances in the fields of neuroscience and therapy and provided an initial platform through which I learned the state of neuroscience research and was able to investigate mentioned topics more specifically. From these books, snippets of the history of neuroscience, neuroplasticity, and even haptics arose and piqued my interest for further research in these arenas and provided a broader lens from which to then gather more specific material.

The paper as a whole is divided into sections to be used in haptics, or it may be used for a broader overview. With this in mind, topics are broken into sections and subsections to make finding material easier. Within the body of the text focusing on research, personal narrative elements and conclusions are largely withheld, focusing on results and conclusions from cited works. Combining these sources into conclusions is done in the Conclusion and Opportunities in Haptics sections, resulting in citations in these sections as well to provide context for the opportunities and combined study conclusions made here. An annotated bibliography is also appended to this work, allowing readers to read my reflections on various materials I read while crafting this thesis.

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Focusing and Engaging the Mind

One of the most overarching and potentially advantageous applications of haptics is in maintaining or improving mindfulness and attention. Studies suggest that our minds wander between 30% and 50% of the time. That value can vary based on activity, concentration, challenge, and mental training, and estimates as high as 70% exist when expanding our definition of mind wandering to any non-task dependent thinking and dream-like thoughts [32, 33, 34, 35, 36]. This makes it clear that there is a sizeable portion of time in which we are not fully engaged or focused solely on a given task. While our minds are less than fully focused, we may miss information, fail to respond to environmental cues, or make errors in decisions and judgements. These lapses could have catastrophic consequences depending on one’s environment – from choosing the wrong answer on a test to operating a motor vehicle in error and causing injury or death. It could even impact our general happiness [32].

Mindfulness training has been shown to potentially reduce how often a person’s mind wanders. This training may be executed using digital technologies like Headspace and Lumosity applications and comparing Sustained Attention to Response Task (SART) metrics and Mindful Attention to Awareness Scale (MAAS) measures. Training may have a positive effect on improving mindfulness and reducing mind wandering, but the different trainings significantly vary in effectiveness [30]. Haptic training has also been studied in short and long term attention trials and through haptic interventions and guidance on breathing, relaxation, and meditation. The addition of haptics has shown a positive effect on all of these metrics [37, 38, 39]. Closely related to mindfulness, attention can also be improved with the use of haptics in general and to support rehabilitation therapies.

Breathing, Meditation, and Mindfulness to Mitigate Stress

Mindfulness and meditation are commonly discussed as methods of maintaining focus and recentering oneself in the present moment. This feeling of presence can reduce stress and anxiety as well as increase relaxation. Haptic-enabled breathing therapy and meditation guidance have been shown to be particularly useful in reducing stress in several studies, and the use of haptics is significantly more efficient at reducing stress than non-haptic methods [39, 40, 41].

An indirect but consistent and quantifiable method of studying stress is through breathing. By improving breathing through therapy, relaxation may also be increased alongside decreases in stress and anxiety. In a study of professionally-supervised breathing therapy, breath rate and volume of ten subjects was studied to examine the efficacy of haptic guidance. Receiving haptic cues contributed to a 40% improvement in therapy outcomes [42].

Outside the clinical setting, phone applications can serve as cuing mechanisms for breathing exercises and breathe regularly. In smartwatches, mobile applications have been developed to facilitate steady breathing and relaxation in a variety of ways. The app Breathe employs the use of haptics to improve user breathing consistency. Users have particularly touted Breathe for its integration of haptic synchronization. While other apps facilitate steady breathing through auditory cues, Breathe provides auditory cues in tandem with haptic vibration cues to pace user breathing [43, 44].

Stress may also be exhibited and quantified through heart rhythms and heart rate variability. By studying electrocardiogram (ECG) data, two separate studies investigated the use of haptics to reduce stress. In one study, users received ultrasonic touch stimulation on their hands, and in the other, breathing cycles were conveyed by inflating a bag under the users’ hands. In both studies, heart rate variability metrics improved more after training with the haptic stimuli than without [40, 41].

Finally, relaxation was studied in mobile meditation apps. As expected alongside other indicative studies, haptic feedback from the applications increased relaxation and de-
creased stress according to user surveys. The novelty of these findings came in the demonstration that haptics alone saw the greatest improvement compared to auditory or haptic and auditory feedback [39].

Maintaining Attention

For maintaining and improving short-term attention to more efficiently complete tasks, haptic interventions show extreme promise. In one study, rhythmic haptic stimulation of a 15Hz sinusoidal signal was applied to subjects’ palms while they completed a Test of Variables of Attention (T.O.V.A.) exercise. This test is used to measure several factors of attention including omission error – the failure to react to target stimuli; commission error – the mistaken reaction to non-target stimuli; and reaction time. Participants in the test group with haptic stimulation to the palm observed a significant improvement to omission error and reaction time, indicating that they were paying closer attention and able to react more swiftly compared to their initial T.O.V.A. metrics. No significant improvements were observed in the control condition participants who were not exposed to haptic stimuli [37, 38]. In other studies, force control tasks were significantly improved with the addition of haptics. Longer-term attention through a variety of haptic-enabled gaming has also shown positive improvements [38].

For populations with Traumatic Brain Injury (TBI), a common effect of the injury is a propensity toward inattentiveness. Patients lose focus on current tasks, have difficulty switching tasks, and get distracted easily [45]. It has been shown in TBI rehabilitation studies that haptic intervention may improve attentiveness and task completion, and help subjects refocus on active tasks. In a study of TBI patients who received visual and haptic training versus standard Attention Process Training, those who had the visuo-haptic training were better able to ignore auditory and even haptic distractions [46]. In another study, by providing a haptic nudge – a 1 Newton, 250 millisecond vibration – when subjects lost focus (as indicated by a cessation of motor activity), TBI-affected subjects completed a reaching task more quickly and frequently [47]. This demonstrates the clinical use of haptics for maintaining attention not only for general populations, but for rehabilitation practices as well.

Educational Engagement

In maintaining educational engagement, a survey of eight classes of middle and high school students indicated enhanced engagement and attention to virus biology concepts in students who received haptic joystick feedback while manipulating viruses [48]. Other works by labs at Johns Hopkins University and NASA’s Langley Research Center have identified better engagement and deeper understandings of simple virtual reality tasks and elementary physics machine concepts [49, 50]. These findings are closely associated with the indication that choice and manipulation of objects and their properties contribute to attention and focus when learning new information [51].

Furthermore, fun and engagement are closely tied together, particularly in the context of education. Serious Games are a classification of game that mimics reality more closely than other games based on the premise and execution of the game. They are often used in education to promote lifelike game simulations with more concrete learning outcomes. In these games, it has been found that enjoyment of the game has a significant impact on learning motivation [52]. Motivation, in turn affects engagement with the content of the game, which is critical in achieving learning gains [53]. Most of these interfaces include only auditory and visual cues. However, incorporating tactile feedback in these games can promote learning outcomes as well.

Tactile feedback and interaction has been linked with more intense feeling and emotion than other senses. Leveraging this, researchers implemented haptic feedback for three Serious Games, finding engagement improvements due to the addition of tactile feedback. Specifically, the learning outcomes related to motor skills are particularly engaged by force feedback, and cognitive skills are also enhanced [53]. In these ways, haptic force-feedback games may be used as an especially engaging learning tool.

Researchers investigating haptic improvements of educational accessibility for children with learning disabilities also observed improvements through games. In parallel with their findings, they particularly highlighted the requisite balance of fun and learning outcomes. In their study, haptic Augmentation was found to enhance enjoyment and therefore motivation and engagement in the learning tools. Some learning improvements were observed, but the researchers noted that further development of the learning methods must be pursued more fully to best engage the attention of children with diverse learning abilities [54].

Capturing Attention

Even beyond maintaining attention, fully engrossing a person in a task has numerous advantages. In a highly stimulating world, it is no surprise that studies seek to manipulate the direction of a person’s attention – as understanding that could not only have task-specific outcomes in improving the time or quality of work, it could also have advertising and economic effects to retain customer attention. Therefore, many industries seek to understand how attention may be controlled for desired outcomes.

As previously discussed, mobile applications of haptics are prevalent. From virtual home buttons to typing, haptics can be used to better control our mobile devices. But phone haptics are used in other spaces too, namely, the gaming and advertising industries. Attention-grabbing gaming haptics have existed for years in the forms of rumble boxes, joy-
sticks, and other controllers. In advertising though, more recent advances and research of haptic advertisements indicate improvements in brand recall (10%), advertisement interaction and replays (30-60%), overall happiness and excitement (7%), and brand perception (6-30%) [55, 56]. With these metrics, it is clear there is great potential in the haptic advertising industry and companies that capitalize on this stand to attain great gains.

**Educational Enhancement**

Haptics have been studied for enhancing learning outcomes in subjects from writing to anatomy, as well as improving accessibility and retention for alternative learners. The area of education, though, is fraught with differing definitions of the term, "haptics" ranging from meanings related to tactics, to kinesthetics, to simulations. Nonetheless, haptics can be used to provide valuable feedback for students to better understand the world around them.

"Haptic" Learning Styles

According to a study by Specific Diagnostic Studies (SDS) of Rockville, Maryland, 37% of students in grades 5-12 are reportedly haptic learners [57]. In another study of undergraduate students by the School of Education at the Colorado State University, the minimum population of haptic learners in any studied undergraduate classroom was 42% [58]. This finding holds across college-aged students. In a review of six other studies comparing the Learning and Interpreting Modality Instrument (LIMI) employed in the Colorado State University study, the LIMI self-reporting survey consistently found that haptic learners accounted for about one-third of the student population. Despite the self-reporting limitations of the LIMI test, its results were consistent with observational studies and grouped reliability tests [59].

This definition of haptics, however, can be deceiving. Rather than artificial tactile sensory stimulation, these studies’ use of the word "haptic" is very general and likely conflated with the terms "hands-on", "kinesthetic", and "movement". In relation to our definitions, these coincide with a more passive tactile environment, rather than the active haptics investigated thus far. In these learning style surveys, “haptics” was one of three learning profiles defined in the surveys. The other two were visual and auditory. In three-group examinations such as these, haptics rarely refers exclusively to simulated feedback through tactile presentation, but more often to active or kinesthetic learning. That is consistent in these studies, with their ranking methods defining haptic learners as those who learn most effectively when moving, making, creating, and experimenting [57, 58, 59]. Indeed, other non-learning-focused studies sometimes use haptics in this way, with a study of attention in children with Attention Deficit Hyperactivity Disorder (ADHD) employing the use of ball games and jump rope classified as "haptic" methods [58].

Despite these definitions of haptics and haptic learning differing from ours in their breadth and their more passive environmental-interaction-based interventions, they do illuminate the limitations of a purely visual or auditory education style. When presented only visual or auditory stimuli, many of these students will not be learning through their primary sensory modality preference. Some of these students may be cross-modal learners; in one college student study, 63% showed a clear single-modality preference, 15% showed dual-modal preference, and the remaining 22% had no clear preference [59]. This indicates that while the full population of kinesthetic learners are not excluded entirely from their primary learning aptitudes when receiving traditional visual and auditory information, some are. These students far prefer and benefit from a “hands-on” style of learning to improve attention, retention, curiosity, and overall learning outcomes, and their learning success is negatively impacted by receiving instruction in styles differing from their preferred learning style.

Although the definition of haptics is not as well matched to the investigations presented throughout this paper, these study findings of varied learning preferences provide an understanding of the multimodality of learning and the ideal learning methods of student populations. Haptics – regardless of the specific definition – does require at least some form of tactile interaction, and these studies indicate that over one third of students learn best from a more tactile sensory education experience.

**Writing Skills**

Despite the frequent conflation of the terms haptic and kinesthetic, some research does focus on the application of sensory simulation through tactile and vibrotactile feedback devices. At a very young age, haptic simulators have been used to improve student handwriting. Handwriting development studies involve kinesthetic handwriting practice for all students, but what is particularly noteworthy and qualifies these studies as simulated haptics is the vibration and resistance feedback provided in the learning processes.

Two prominent articles have addressed supplementing handwriting training with haptic feedback. A study published in 2006 introduced an interface for providing haptic, audio, and visual feedback for learning and writing letters. With this technology, learners of five written languages could be redirected if significant deviation occurred. The con-
trol session was unguided. The results of this study show that with haptic feedback training, the six study participants were able to consistently replicate given letters with less than 5.8mm of error between the taught trajectory and the executed trajectory. Furthermore, their application of force was smooth, and experienced no sudden changes. After only two trainings, three of the six students wrote all ten trained letters without error. Two wrote all but one, and one student made two errors. These results show promise for this haptic guidance technology in early elementary education [60].

In the following year, another study using the Phantom interface device and investigating writing in kindergarten children was published. In this study, 42 kindergarten students were studied while learning to write a letter on a computer screen by controlling a Phantom pen extension. With a control group of 21 students and a test group of 21 students, the haptic test group wrote the letters significantly faster, with more consistent velocity, and had fewer breaks in writing than those trained with identical visual feedback but without haptic feedback [61].

STEM Education

Haptics in the form of small-scale modeling and enabling learners to simulate and manipulate their environments are especially prevalent in STEM fields in which simple physics machines, chemical models, and other physical representations exist. Some of the easiest implementations of haptics to imagine are in small-scale modeling. Atomic structure representations for physics and chemistry and cellular models in biology are two such examples [62]. Physics is also a particularly prominent field of supplemental haptic models as a method of reinforcing various topics. In a study by Jose et al., elementary school students tested enhanced physics computer simulations for four key phenomena – gravity, magnetic force, frictional force, and viscosity. Weight and resistance via haptic simulation feedback were provided in parallel to computer visualizations. The tools were developed for users with visual impairments, but the study revealed enhanced learning for all learners through multimodal feedback, engagement and interest, and increased complexity [63]. Further physics-based studies have been performed with students investigating simple machines and their associated kinematics and behaviors [50].

Beyond elementary classrooms, haptic simulation in undergraduate and graduate coursework has also proven to be rewarding. In the study of anatomy, manipulating organs and other body parts is made possible through haptics. Not only can one visualize the organs, they can interact with them without ever leaving the classroom or cutting into a live organism. Through the use of a Phantom Omni, users in one study were able to manipulate and explore 3D models and simulations of tissue to better understand anatomical organs. Through these methods, users reported ease of use, learning enhancement, and physical and mental ease as primary benefits to this technology [64]. Haptic supplements for anatomy education can be even simpler than 3D models of organs and tissue. Another study at the University of Cape Town suggests that a “haptico-visual observation and drawing” (HVOD) method was successful in improving students’ memorization of anatomical structures and properties of human body anatomy using only 2-dimensional methods [65].

Education Accessibility

Haptics can also break down barriers in education. Haptics can provide enhanced accessibility to learning materials for visually impaired students and those of other abilities. Unfortunately, accessibility of education is not a heavily studied topic in the field of haptics. Most research of disability and haptics centers around three main tenets: computer usage, wheelchair and robotic control, and adult rehabilitation [66].

Haptic interfaces for blind users are more studied than others. For computer interfaces, haptic systems are particularly developed to improve usability and manipulation techniques for blind and visually impaired users. At the middle school level, applications and computer simulations especially focus on STEM integration. Over 20 specific computer applications have been developed for blind learners that convey a variety of topics including 3D object manipulation, interacting with atoms, plant cell exploration, lessons on volcanoes, and many more. In a study of three classes of blind middle school students at the West Virginia School for the Blind, all students reported a better understanding of the material presented through computer haptic applications. Students were eager to learn the material, and after a short training period were largely able to work independently with the computer applications [67,68].

Haptics also provide improved access for adult users who are blind. For graphical representations of scientific and mathematical data, applications have been developed to construct and examine complex data [67]. Graphical representations may be made more accessible for users of all ages with haptically simulated 2D and 3D data, line plots, surface plots, bar charts, pie graphs, maps, and other data representations. Textural representations have also been used to convey additional data dimensions, which could be extended to differentiate data sets, as sighted people do with color [69]. For scale and overall context, 2-dimensional grid lines provide localization information for more robust analysis for visually impaired users [70].

Attention, as discussed previously, can be improved through the use of haptics, and the positive effects of these technologies for differently abled populations persists. Improving attention and engagement in populations suffering from TBI through haptic force feedback showed statistically significant improvement compared to those without haptic
feedback [38]. In other populations such as those with Attention Deficit Hyperactivity Disorder and Attention Deficit Disorder, significant attention improvements were observed with force-based association training as well as with force control and feedback tasks. Complex movement tasks using haptic feedback also show great promise for improving concentration and attention control [38].

For individuals with more diverse disabilities, educational enhancements through haptic methods are less straightforward because the range of disabilities and interactions is more broad. Nonetheless, learning outcomes of educational haptic games have been studied and surveyed, as have applications of tactile stimulation for individuals with Autism Spectrum Disorders [54, 71]. A prominent difficulty stated in these studies is the diversity of presentations of the disabilities and the balance of engagement methods with concrete learning outcomes. Nonetheless, research of haptics for improving accessible learning modalities is critical in order to leverage all available resources to improve access for all people.

Haptics for Training

Some may view education as a form of training for future life. While examples of the benefits of haptic education supplements exist, the benefits to specific skill training are even more studied. Especially in high-risk jobs, simulated environmental training is critical in learning the skills for the trade before being exposed to the risks associated. Two such examples are medical training – where the risks are external but very high, with medical professionals and particularly surgeons being acutely responsible for the life and death of a patient – and flight training – where the risks are initially more personal including risk to the trainee and perhaps a flight instructor, but where downstream ramifications could affect travel outcomes for hundreds of travelers at any given time.

Surgical Training

Surgical training enhancement has been studied through multiple modalities. Likely the most studied enhancement is in the field of Minimally Invasive Surgery and laparoscopic surgery. Laparoscopic surgery is a type of minimally invasive, camera-assisted surgery in the abdominal region using a long tube called a laparoscope. Through the use of cameras, surgeons may observe this miniaturized surgical equipment and perform complex surgeries using less invasive procedures which reduce the possibilities of surgical complications. Post-surgical complications are reduced here due to a smaller incision and more locally precise internal surgical execution; however, a surgeon has a much smaller area of operation, presenting benefits as well as difficulties. In laparoscopic surgery, every motion the surgeon makes must be well calculated to be positioned precisely and exert the perfect amount of force. Sensory feedback is limited because the surgery is taking place well within the body under multiple layers of skin and tissue, through an incision only as large as necessary for the equipment itself to fit through. Therefore surgeons must rely on the visual feedback of the cameras and the force feedback of the instruments as the only two sensory feedback mechanisms.

In learning the surgical techniques for laparoscopic surgery, a major limitation is the difficulty to practice the skills required in a low-pressure situation. Unless one is operating on a live patient, there is limited realism to the surgical training. Even when operating on a live patient, feedback can be limited based on the small scale of surgery and physical distance from the surgical site due to the use of laparoscopes.

Most training is done in digital simulations with feedback given by a screen with an animated probe position display. The instruments used in this simulation give little to no feedback – only the weight of the instruments themselves – with no realism to the simulation of tissue interaction. One way to improve this simulation is through the use of haptics. To provide this feedback, the laparoscopic instruments in the training contraption can be made with vibrating motors in order to provide a sensation to the trainee of encountering tissue. In these examples, vibrotactile feedback may simulate the act of penetrating a tissue wall or moving through organs of different densities.

In a study by Zhou et al. investigating initial laparoscopic training with participants having no experience performing laparoscopic surgery, it was observed that haptic feedback improved consistency and initial training speed. However, of particular note was the finding of a training plateau that was observed in both haptic-informed and non-haptic-informed trainees. Those using haptics reached this plateau earlier than those without, indicating that initial training could be a particular use for haptics in this area, but that given ample time and training, populations trained with and without haptics may reach similar levels of skill acquisition when initially exposed to laparoscopic skill training [72].

Studies of laparoscopic training later in a person’s medical career indicate that haptics may continue to contribute to enhanced performance later on. A study of medical students and surgical residents investigating varied graspers for laparoscopic surgery found in 2017, that enhanced haptic feedback in the surgical instruments significantly improved instrument and tissue interaction, reducing the force between them. This study featured skill training on real organs, demonstrating the applicability of haptic techniques to real tissue trainings and extending to live surgeries as well as training protocols [73]. In another study in 2019, a 3D simulation task was provided for experienced surgeons to develop and improve their laparoscopic surgical skills. In this study,
surgeons performed a suturing task with and without haptic feedback. Interestingly, study participants self-reported that the trainings were unrealistic, but by performance, those with haptic-enabled instruments demonstrated significantly less tissue damage from stretching the tissues than those participants who did not have haptic feedback [74]. These results indicate that haptic interfaces for advanced laparoscopic training may contribute to less tissue damage and fewer surgical complications, improving the safety and success of these types of surgeries.

Perhaps the reason for this resurgence of usefulness in haptic training after initial training is due to the cognitive resources available in a surgeon’s mind after the initial training stage. In another study by Zhou et al., it was found that the more experienced a surgeon was, the more their performance benefited from the addition of haptic feedback. This study included 30 surgical residents and attendings evenly distributed across experience levels from 1-year post-graduate to fellows and attendings who had been practicing medicine for at least 6 years since graduating medical school. Overall, exaggerated and normal haptics resulted in faster and more accurate performance of laparoscopic surgical tasks. The novelty of this study was its investigation of surgical task completion while under cognitive load in the form of math problems. While under cognitive load, subjects performed more slowly than without cognitive loading, but maintained their accuracy. However, the relationship between non-haptic and haptic feedback remained as before, with faster and more accurate completion by those with exaggerated and normal haptic feedback. This strongly indicates that the improvement from haptics is greater than the effect of cognitive load and that haptics can improve performance regardless of cognitive resource availability. Furthermore, it was seen that more experienced surgeons performed faster, but not more accurately, than less experienced surgeons. For these experienced surgeons, their improvement in speed was more dramatic with haptics than the improvement of less experienced surgeons, indicating they may have had more spare cognitive function available to fully leverage the haptic feedback that was provided [75].

Haptics have also been used for needle insertion training, particularly in investigating tissue boundary detection via vibrotactile haptic simulations of boundary breakage versus visual observation of piercing the same boundary. It was found that visual feedback alone is more beneficial than haptic feedback alone, likely because it is more immediately perceived. However, haptics may be used when visual feedback is unreliable or as a supplement to visual feedback [76].

Dental surgery is another potentially high risk skill with limited training simulation realism. In a situation in which too much force may result in overdrilling a tooth or even tooth perforation, and too little force may cause irritation and allow the formation of necrotic tissue, training students with force feedback is critical to gain the ability to accurately determine how much force to apply during dental surgeries. Furthermore, these force applications can be as small as one tenth of a Newton. In a study presented in 2017, comparisons were made between dental training for students with and without haptic feedback in the training simulation. Those with haptic training feedback showed significantly improved training outcomes compared with the control non-haptic group who received feedback only regarding the outcome of the training execution from an endodontic instructor [77].

**Flight Training**

Haptic training applications are clearly useful in training new surgeons and other medical professionals in low-stakes environments. Another high-importance, high-risk area of task execution is in maneuvering aircraft. Two dynamic factors are at play in the safe operation of most aircraft. Most critically – the knowledge and skill of the pilot is a dominant factor in the overall safety of air travel. A pilot must know all the facets of flight and the equipment available on a given aircraft. The second less-obvious but perhaps even more critical factor is cockpit and flight deck familiarity. Pilots must be trained in each new aircraft they fly in order to learn and know the control layout just as well as knowing the actual maneuverability of the plane. A pilot in an unfamiliar cockpit can present as much danger as a novice pilot in a well-known cockpit.

To gain the skills of flying and controlling an aircraft, virtual reality flight simulators are the most direct avenue for simulating flight experience and flight control execution. The accuracy and realism of these simulators is critical in the transference of both skill and operator ease in a real flight situation. Typically in these simulators, the joystick, throttle, and pedals are the only live elements of the system. No other tactile controls are available. Rather, all controls are simulated and until recently, the only confirmation of having activated a control was through visual channels. However, in 2018, the French company Go Touch VR piloted the adaptation of pressure sensors to provide control feedback in these flight simulations, allowing users to know they had successfully activated a control without the mental distraction of having to visually track and confirm task execution [78]. Expanding from this, ultrasonic mid-air haptics have been developed to allow motion tracking and simulated tactile control interaction, giving the illusion of physical equipment without its presence [21].

In these virtual reality simulations, the instrumentation orientation is also critical – providing an avenue for pilots to familiarize themselves with the locations of their equipment. The cockpit layout of an Airbus A320 aircraft, for example, differs from the cockpit of a Boeing 747, which in turn differs from a Boeing 787. These considerations present an espe-
cially great need for virtual reality controls to be adjustable and able to emulate any given cockpit layout. This increases the importance and opportunity presented by haptic feedback simulators that are dynamic and adjustable [21].

One more consideration of aircraft control lies in the amount of information that must be considered at every point during a pilot’s operation of an aircraft. With all the controls, sensors, displays, and other environmental factors cluttering a pilot’s visual field, conveying status information in a non-visual format presents a unique opportunity to reduce a visually overwhelming environment. Auditory stimulus is one avenue that is occasionally used, but it is typically limited to critical alerts. Haptic interventions can provide integrative feedback about individual sensors in a location-specific setting in order to only provide sensor data that affects the current control operation. Pilots in one study successfully controlled a simulated flight while simultaneously receiving tactile representations of the simulation’s sensor data [79]. In quantitative comparisons of haptic force feedback, pilots were able to maintain flight simulation altitude using tactile-only stimuli without any visual feedback. As one might expect, tactile feedback alongside full visual cues showed the best performance, but demonstrating the ability to perform this task with little error and without any visual cueing shows the potential to simplify cluttered visual cockpit displays [80]. In studying flight performance improvements with the addition of haptics to a classic control and monitoring system, overall performance is improved significantly with haptic force feedback. The results showed over 20% reductions in tracking error and pilot-applied force [81].

An opportunity for development in integrating virtual reality cockpit simulations and improved control performance exists in virtual reality live cockpits. As Air Force engineers added adjustable control pedals, seats, and flight gear to cockpits in the 1950’s and observed a dramatic improvement in pilot performance, a virtual cockpit in a live plane could allow enhanced adjustability and improve performance [82]. A more virtual cockpit allows an individual pilot to customize a cockpit’s controls and control locations to suit their needs and their mental map of controls. Rather than having to completely reorient one’s self to a new layout every time a new cockpit is entered, a pilot could transfer their preferred cockpit with them in order to reduce errors caused by unfamiliar control layouts. Using morphing controls as already seen in parts of the automotive industry, this could be further improved to reduce visual overload by using virtual control morphing to switch which controls are most centrally accessible based on current needs [83]. All of this alongside haptic force feedback could dramatically improve flight safety.

Implementing haptic cockpit technologies beyond a flight simulator obviously requires much more testing and analysis than has thus far been completed. Maintaining simulation height and improved system knowledge and response are only two of the many tests that must be undertaken. In transitioning haptics from training scenarios to real-world implementations, perhaps further research of the automotive industry may provide a larger sample of data and a more diverse user and emergency profile. The research in driving is also limited but provides more statistically comparable metrics of error avoidance. Lane Departure Warning Systems have shown that haptic alerts exhibit distinct improvements over auditory cues. Alerts for time-critical collision events have also revealed marked success in driving performance. Using simple, binary haptic alerts, driving attention, behavior, and collision avoidance have been improved, showing the potential for relatively simple haptics to improve safety [84]. These same principles could extend to aircraft to better improve pilot performance and flight control.

**Haptic Rehabilitation**

Medical rehabilitation has also been investigated using haptic interfaces and tactile stimulation. Rehabilitation can range from physical therapies to sensory substitutions, all with the goal of enabling people to recover more swiftly and completely from injury or illness.

Many interventions in recovering lost skills leverage neuroplasticity – the ability to reconfigure brain neurons to perform different functions than were originally learned. One of the biggest names in neuroplasticity rehabilitation is that of Paul Bach-y-Rita. A neuroscientist and designer, his work has advanced research and conceptions of neuroplastic reorganization immensely, particularly through the lens of sensory substitution. Sensory substitution is the ability of one sensory system, say the visual or auditory systems, to be replaced by another. According to Bach-y-Rita, "We don’t see with the eyes. We see with the brain." [27]. In fact, he argues, all senses are rooted in the mind and the five senses are not distinct or independent of one another. In this way, any external sense may be redirected to take the form of another in the brain and give sight to those who are blind, sound to those who are deaf, and more.

Bach-y-Rita’s three main focus populations were blind people, people with balance issues, and people who had suffered a stroke. His initial breakthrough in neuroplasticity came from the medical examination of his father’s brain in 1965. His father, Pedro, had suffered a cerebral infarction, or stroke, in 1959 causing paralysis to half his body. Paul’s brother, George, was a medical student at the time, and through elementary exercises such as crawling, playing games on the floor as a child does, and washing pans, he helped his father regain the ability to walk, talk, eat, type, and even teach, functioning as if he had never had a stroke. When his father died, his body was brought to San Francisco, where Paul was working. Paul requested that an autopsy be performed, and through this, discovered that his father, though seeming to have regained all the motor and psycho-
logical functions he had lost by the stroke, had never regained the neural function of that region of his brain. Unknowingly, George had helped his father develop new neuronal connections and functions to perform all his desired activities despite his brain never recovering from the stroke.

Paul reports that when seeing the significant damage to his father’s brain stem despite regaining all function, "I knew that meant that somehow his brain had totally reorganized itself with the work he did with George. We didn’t know how remarkable his recovery was until that moment, because we had no idea of the extent of his lesion" [31 p. 23]. This moment marked the start of Paul Bach-y-Rita’s career focused on neuroplasticity and teaching the brain to function in new ways.

Sensory Substitution

Focusing on leveraging principles of neuroplasticity, Bach-y-Rita was confident he could reorganize and reorient the brain to perceive senses in different ways. His first major invention allowed blind people to perceive visual data. Specifically, Bach-y-Rita repurposed a dentist’s chair into a mechanically operated vibrotactile stimulation device. It included 400 vibrating plates embedded into the back of the dentist’s chair in an array much like a 400-pixel screen [85, 31, p. 14].

The initial proof of concept of this sensory substitution of vibrating tactile devices replacing lost eyesight was transformative to participants who could now identify objects, motion, and identities of individuals, as well as read. However, this device was inconvenient and not at all portable. Although the sense of touch is typically associated with the fingers and limbs, future iterations of this “tactile vision” system included an array of electrodes upon the tongue. Tongue stimulation was able to provide similar feedback such that motion, color, or other observable qualities which most people think of as being vision-specific could be perceived [27, 28, 86, 87, 31, p. 20].

Bach-y-Rita went on to design countless sensory substitution methods and apparatus including a high-resolution, feeling glove for astronauts of NASA, and a similar glove to enable blind people to read computer screens. He developed a device to sense orientation underwater, and a tool for surgeons to perceive the exact orientation of a scalpel [31 p. 20-21]. These varied applications demonstrate the power of sensory substitution and particularly the ability of vibrotactile haptics to convey information to replace other senses.

This is not to imply that sensory substitution may only substitute tactile feedback for vision. Numerous technologies exist for other substitutions including auditory input in place of visual input. One such technology is the vOICe soundscape device that scans the visual field from left to right and converts it into sound profiles [88]. There are individuals around the world and throughout history like James

Hollman and Daniel Kish who develop their own techniques of echolocation-like feedback to sense their surroundings through sound despite their blindness. Their sightless experiences include traveling all over the globe, bicycling, and countless other types of activities [27, 89]. For other senses, haptics are common to replace sound feedback. Bass in music, for example, is commonly cited by deaf individuals as a way to experience sound and music. Visual sensory replacements for sound exist as well [90, 91]. Nonetheless, haptic response is one of the most prevalent in substitution techniques because it provides an otherwise underutilized sense for detecting more distant stimuli [92].

Balance Therapy

Building off of his work in sensory substitution, Bach-y-Rita used the principles and technology of tongue sensory stimulation for the rehabilitation of balance and motor skills. For patients who had lost their sense of balance due to side effects of chemicals such as those used in chemotherapy and antibiotics, Bach-y-Rita developed a device to assist in sensing when one’s head was level versus when the individual was falling over by using a haptic tongue stimulation device. These types of balance issues plagued Cheryl Shiltz, whose balance was severely impacted after taking the antibiotic gentamicin, which damaged her inner ear. This made it feel that the world was constantly spinning even when she was laying down. However, Bach-y-Rita’s device allowed her to regain the balance sensing she had lost.

The electrode array employed for balance rehabilitation by Bach-y-Rita was similar to his “tactile vision” tongue device, and it has since been developed commercially as the Portable Neuromodulation Stimulator (PoNS™). These haptic technologies leverage the sensitivity of receptors on the tongue and its proximity to the brain stem to improve balance [28, 93]. Bach-y-Rita’s device was composed of an electrode array identical to the “tactile vision” device, but instead of vision, it conveyed information similar to that of a carpenter’s level. When a subject was upright, the device’s central electrodes were activated. When tilted, side electrodes were activated informing the user which direction they were tilting and allowing them to correct their positioning to maintain an upright position. Through training, Cheryl Shiltz was able to sit upright, stand, and walk, all of which had previously been nearly impossible. She trained with the device until she redeveloped a sense of balance independently and was able to function without the balance device itself. Through these haptic tongue stimulation technologies, patients with Traumatic Brain Injury, Multiple Sclerosis, inner ear injuries, and more can regain mobility and function.

Most interestingly, Bach-y-Rita himself later underwent chemotherapy for lung cancer which damaged his inner ear and balance system. Shiltz taught him to use the device so that he also relearned how to balance despite the loss of
function of his vestibular inner ear balance system \[27\].

**Stroke Recovery**

After his father’s recovery and the discovery that his brain rewired itself to complete all desired functions using new regions, Bach-y-Rita focused on neuroplasticity, sensory substitution and device development for sensory stimulation. The advances in stroke recovery came from others, including Edward Taub, who set the stage for others to better investigate haptic therapies.

Taub began his investigation of neuroplasticity by studying monkeys and their response to sensory deprivation of nerve [4]. These monkeys, later named the “Silver Spring Monkeys”, underwent a process called deafferentation so that their arms were not fully functional. In this process, incoming sensory nerves are severed such that the brain receives no input from the deafferented nerves. While these monkeys’ deafferented limbs no longer had any tactile feedback, their study has revolutionized neuroplasticity, neural reprojection, and haptic research, and directly impacted haptic device development in the years since.

Taub himself expanded his observations of tactile-disabled monkeys to inform treatment mechanisms for stroke patients through “constraint-induced” therapies. This involved the forced usage of a disabled body part by being unable to use the unaffected, fully functioning equivalent body part (i.e. being forced to use the left hand that has been affected by a stroke by constraining the right hand). In this way, Taub quite successfully rehabilitated numerous stroke victims at his Therapy Clinic. These therapies relate far less to tactile feedback, but rather to neural representations, plasticity, and constraint-based training [31, p. 98-116].

Other researchers have focused on and identified methods to improve function in stroke victims using perceived tactile feedback and devices. The focus of this research mainly revolves around force feedback from computer simulations to regain hand and finger motion acuity. Extensions of these small-scale movement programs have also been developed to regain a larger range of motion. In one pilot study, a computer pinch simulation task was studied for usability and clinical improvement in stroke patients. Of the two stroke-affected patients studied, both observed improvements in task completion time and success rate. Moreover, user adoption and usability was high in these two patients as well as a larger healthy subject group, demonstrating the potential positivity of a larger clinical trial [64]. Another pilot study was developed to rehabilitate fingertips motion, thumb and finger coordination, full hand motion, wrist and forearm motion, arm and shoulder motion, and limb and torso motion. All of these motion scales were reviewed positively by patients and healthcare providers [95].

For more quantitative, controlled data, a study in Sweden investigated prolonged training in a computer-based virtual reality system. In this setup, users received haptic force feedback from a handheld stylus. Each subject’s arm reaching ability was compared to baseline testing. In their five study patients, reach velocity significantly improved alongside reductions to both the time needed for completion and the magnitude of superfluous motions to reach a target [96].

A final stroke rehabilitation study investigated haptic robot usage in fifteen patients using finger and wrist mobility tasks. Their findings indicate that time for task completion and jerkiness of motion were significantly improved using the force feedback robot simulator. Furthermore, it was shown that cortical activity in the brains of these patients, as measured by functional magnetic resonance imaging (fMRI), was improved to more closely match normal brain function for task execution [97]. These results show that improvement can be achieved not only in physical skill, but in mental performance as well.

**Phantom Limbs and Prosthetics**

When a person sustains a traumatic injury resulting in limb amputation, there are both physical and mental changes that are associated with the loss of the limb. A particularly interesting region of the brain studied in this situation is the cortical homunculus. This region of the brain contains an internal representation of the body. There are sections representing the arms, legs, fingers, toes, face, nose, genitals, and other specific body sites [25]. Understanding this region has significant ramifications for therapies of all kinds, but most notably for amputees.

In Taub’s Silver Spring Monkeys, Taub and his associate Tim Pons\(^1\) studied the mental response of the monkeys over time and found that instead of observing decay in the regions of the homunculus for the deafferented limbs, that section of the cortical homunculus had instead developed a response to facial stimulation [98, 31, p. 129]. Therefore, despite the loss of all feedback from their deafferented limbs, their homunculus representation of their remaining feeling regions expanded.

Enthused by this evidence of the brain’s adaptability to more closely match the existing body and feedback schema, neuroscientist V.S. Ramachandran wondered if this same phenomena might be present in humans who had lost limbs. He hypothesized that amputation might be neurologically similar to the monkeys’ deafferented limbs. Furthermore, he was curious whether the mental response to the remain-

\(^1\) Taub’s work with monkeys also contributed to Taub being blacklisted by the scientific community for many years early in his career. Much of Taub’s work was delayed and discredited by PETA – People for the Fair Treatment of Animals – because of his work manipulating monkey’s sensory abilities.

\(^2\) Tim Pons has no found relation to the PoNS neuromodulation medical device.
ing sensory location might indicate a parallel sensation in the amputated limb.

Ramachandran was successful in identifying a similar sensory adjustment in humans whose arms had been amputated. By using a Q-tip, Ramachandran identified that, similar to the Silver Spring Monkeys, his first human patient’s amputated arm had been reprojected to his cheek so that upon stimulating his cheek, the patient felt it on his missing arm. Ramachandran extended this simple study to a magnetoencephalography (MEG) scan and identified that indeed, the patient’s hand map had been transferred to the cheek [31, p. 129].

Further studies by Ramachandran and others delved more deeply into the concept of phantom limbs and phantom pain – the experience of still having an amputated limb and experiencing pain in that limb, which is experienced by an estimated 80% of amputees [99]. Researchers often address this by leveraging the transference of the homunculus’s body representation onto a remaining body part. Through physical stimulation of intact body parts and illusion, amputees with phantom limbs have been able to reduce pain and reduce the obtrusiveness of their phantom limbs. In some cases, phantom limbs have been completely removed from a person’s mental body schema using these therapy techniques [31, p. 130-132].

One commonly known illusion is the mirror box. In this contraption, a mirror is placed inside a box and a person places one intact hand in front of the mirror. The reflection of that hand in the mirror is located where the other hand should be. Even for individuals with two fully functional limbs, this can be a powerful illusion technique. For unilateral upper limb amputees, the illusion may be used to trick the brain into believing the amputated limb remains and may experience the same motion and even tactile sensation as the observed limb [100, 31, p. 132-133].

In a study of virtual reality using a visually immersive Oculus Rift headset, haptic feedback for the intact limb reduced phantom deafferentation pain by a statistically significant 41% as opposed to 28% without haptic feedback. The haptic feedback in this study was provided to the intact limb using vibrating motors, while the user viewed a virtual reality image of two intact limbs reaching for an object. Most interestingly, the intact limb’s tactile perception resulted in the illusion of tactile sensation in the phantom hand [101].

Further illusions on the amputated limb’s stump may also provide relief to phantom pain. By providing tactile feedback upon the residual limb near the amputation site, users were able to sense the presence of their amputated limb. Based on the amputation site and the array of illusory tactile actuators, different illusions provided different layers of believability and success in different patients [102].

Without any involved illusions, haptics may significantly improve phantom pain in amputees learning to discriminate tactile vibration upon their residual limb stump. In a study by Flor et. al., amputees improved their ability to distinguish location and frequency of vibrotactile stimuli from pre-testing to post-testing after training. Furthermore, their phantom pain was significantly reduced, and their trauma-induced cortical reorganization was also significantly reduced [103].

Prosthetics themselves with haptic feedback may provide additional relief to phantom pain. By providing force feedback based on prosthetic grip strength, Dietrich et. al. measured a 47% decrease in phantom limb pain. They also measured a 70% increase in goal attainment. This showed that tactile stimulation not only significantly reduced phantom pain, it also increased the functionality and usability of the prosthetic in order for the user to better understand and conceptualize what their prosthetic was doing [99].

This study illuminates the other main focus of prosthetic haptic research – improving functionality. Increased prosthetic functionality from haptics has been studied in both upper and lower limb prosthetics, and limited functionality is the most cited reason (33% of respondents) for reduced prosthetic usage [104]. Lack of tactile stimulation is also noted to be one of the key reasons for the high rates of prosthetic rejection [105].

Improving functionality and task performance through haptic feedback has been shown beyond the investigation by Dietrich et. al. [99]. In a wrist positioning task, participants saw significantly greater success rates and significantly smaller errors with haptic feedback than without [105]. In a virtual egg task, improvement in motion acuity and specificity was measured in patients who received vibration feedback upon initiation and loss of contact upon their prosthetic fingertips. This study demonstrated a highly significant reduction in the number of broken test “eggs” with haptic feedback than without and a higher number of successfully transferred “eggs” [107]. These studies, and those discussed for phantom pain demonstrate that tactile feedback can significantly improve pain and functional outcomes.

Conclusion

We have seen again and again that haptics are most useful not to replace other senses, but as a supplement to them. When compared side-by-side, performance with vision-only feedback surpasses haptic-only or auditory-only feedback in nearly every study found. However, visuo-haptic feedback surpasses any sense in isolation, indicating that haptics for confirmation can dramatically improve performance. Additionally, when vision is limited or inaccurate, haptics can provide an unobstructed platform of getting supplemental data to inform a user’s actions and fill in gaps in the visual space.

This hierarchy of senses makes sense from a neurological perspective, with studies finding that visual processing occupies about three times the cortical space and neuronal activity than tactile or auditory processing [3, 5]. Vision can...
also convey feedback information faster than other senses, allowing a quicker reaction [76]. With such a high resource concentration and quick response time, other senses are understandably relegated to serve as back-up and supplementary information pathways.

This in no way discounts or diminishes the use of haptics and other senses to better inform us of our environments. It only serves to remind us that we are multisensory beings that take in information simultaneously from many sources. Haptics provide multimodal feedback, so while haptic response is not our fastest, it does provide valuable confirmation and feedback in sensory-deprived situations [16] [75] [76]. Multiple sensory perceptions also lend to more generalized cognitive understandings of represented schema, allowing users to more completely understand their environment, gain new skills, and develop more robust perceptions of concepts [51].

This does not mean that haptic interventions should be used in every scenario. Like any technology, a cost-benefit analysis should be done, not just considering economics and implementation methods, but considering the mental load of presenting multiple stimuli [72]. In some situations, additional sensory stimuli advantage more advanced users who have the mental capacity to capitalize on the additional information provided by haptics [75]. In other contexts, the risk of overstimulation is large. The addition of haptics on top of visual and auditory stimuli has been met with limited improvements and even deterioration of outcomes. By adding all three, it appears that a cognitive overload is reached such that performance is reduced and perception of the task is negatively affected [17] [108] [109] [110].

Overall, balance is key. A "sweet spot" of sensory stimuli must be found to provide maximum benefit. That benefit can be in the form of focus, stress reduction, education, skill acquisition, skill enhancement, simulated environments, muscular enervation, motion therapy, sensory substitution, rehabilitation, and many more. As the market of haptic actuators and software integration grows, the cost of testing sensory feedback interventions will decrease, allowing more optimization of haptic and other sensory modalities to provide the best performance outcomes.

**Opportunities in Haptics**

Haptics is a growing field that has only more recently come into focus as a space for development. Apple, one of the leading companies in innovative technologies, only began recommending the use of haptics in applications through their proprietary "taptic" device with the late 2016 release of the iPhone7. Prior to that, the Apple developer guidance recommended avoiding the use of haptics, reserving them for accessibility features and notifications only [10] [111]. That reservation for special circumstances seems to be built from the concern that haptics can easily overstimulate a user, which is indeed a possibility [109] [110] [111]. However, haptics do provide beneficial stimuli to inform and confirm information from other senses, and when those other senses are potentially unreliable, haptics emerges as a strong candidate for replacing limited or dubious feedback [16] [76]. Haptics also outperform other senses when there is a high mental or physical workload, which could be extended to improved working relationships with our phones and other technically demanding devices [17] [75] [108].

**Research Opportunities**

One of the major limitations to research in haptics is the lack of standardized definitions. This results in fields like education having a strong "haptic" body of research, but that research relating more closely to motion and kinesthetic learning than to tactile sensory information transmitted to simulate or exaggerate environmental data [57]. Further research in haptics and haptic devices could present excellent opportunities for more device development and testing in a student population already familiar with miniaturized representations and devices but currently unfamiliar with the opportunities and outcomes that may exist in haptic modeling and manipulation.

Much of the training research I encountered was medical in nature. This is a highly valuable field for research because of the risk of undertraining and the limited opportunity for realistic, low-risk surgical environments. In this field, the enhanced feedback provided by haptic training simulators and haptic exaggeration instruments is intuitive to implement, and easier to quantitatively measure performance improvements, but it is far from the only field in which haptics may be deployed to enhance outcomes. As seen in the flight simulator studies, airplane control may be improved. However, quantitative data comparisons remain lacking in this field [80]. Driving assistance technologies, are slowly entering the car market with Lane Departure Warning Systems, attention alerts, and collision warnings. These could provide a valuable demonstration of haptic efficacy and measurable data on collision avoidance and other control measures. It also could be an avenue of significant growth in haptics for consumer products by providing haptic interfaces for the general public [17] [84]. Beyond these specialized cases, training for more general cases could be well-served by further research attention. Lab training, woodworking, hunting, and even sports technique development are fields that come to mind as opportunities for research and growth in haptic implementations because they present initial risk to trainees, have steep learning curves, there is limited access to practice environments, or they require consistent maintenance of skills.

For rehabilitation, especially in amputees and prosthetic users, haptics research is split between replacing lost sensory feedback, providing reliable prosthetic feedback, and reducing pain and cognitive dissonance through haptic stim-
ulation. Fully replacing sensory feedback realistically comes very close to creating virtual realities and their associated environmental conditions. There may be great strides to be made in this arena, but more advanced devices must be developed first. Instead, further research at this time should be directed towards investigating how illusions may be created through simple stimulation and how the brain processes different senses and combines them to create a representation of one’s environment. For pain reduction, devices must be made more accessible for users to do product testing because although studies indicate positive impacts, the subject sizes are often too small or otherwise limited to make real impact in the rehabilitation or haptics research communities.

Finally, researching how haptics can encourage other action or associations should be further developed. For example, some suggest that educational benefits from haptics are really the result of multimodal feedback or opportunities to interact with the information over a longer time and with more novel tools. In movement rehabilitation, it has been argued that haptic training induces movement and it is movement, not haptics, that promotes rehabilitation success. Neither of these are reasons to stop pursuing haptics. Instead, further research must be done to decouple these outcomes. How do haptics encourage different forms of learning? How does the novelty of haptic technology affect outcomes? How do haptic devices promote movement in limited mobility populations? How do these outcomes in turn promote academic or rehabilitative successes? If haptics can be used to encourage a behavior that then improves outcomes, research must be done to better understand how we can better target development and further leverage these chain reactions.

Implementation Opportunities

So much focus is on immersive reality and emulating existing environmental realities, but limitations in current haptic actuation technology will limit the realism of simulations. I propose that just as much focus be dedicated to non-immersive haptics. We have seen the usefulness of haptics in maintaining or directing attention using subtle, non-immersive, simple vibration techniques \[37\] \[38\] \[112\]. They can be used to improve steady breathing, reducing stress and anxiety beyond the specific time of use \[42\] \[39\]. Haptics have also been shown to improve education and skill training outcomes with simple haptic enhancements for manipulating simulated environments and exaggerating existing forces \[50\] \[73\]. Finally, simple vibrating motors have been used to replace senses like vision entirely, and to create illusions of feeling and sensation where none exist \[85\] \[29\]. All of these demonstrate the power and potential of simple haptic techniques without the need for fully immersive environments.

Acknowledgements

A tremendous thank you goes to Professor Frank Durgin, Thesis Advisor and Professor Maggie Delano, Engineering Design Project Advisor.

References


[44] “4 apps and devices making the most of haptic technology,” 06 2016.


[55] T. Wasserman, “Major brands get hip to haptics,”


[83] C. Automotive, “Morphing controls.”


Annotated Bibliography

References


This is a 10 minute video about Paul Bach-y-Rita’s tongue stimulation device, which is similar to the PoNS devices. It provides a valuable preview into the subject of portable neurostimulation and how visual information may be represented and understood through tongue sensation.


This popular culture blog post reviews four applications of haptics that are revolutionizing the industry. The four focus technologies are a watch that uses sonar for visually impaired users, robotic surgery with haptic feedback, Apple Watch breathing and mindfulness technology, and ultrasonic air-based haptics (i.e. without any mechanism touching the skin to provide tactile feedback).


This web page presents findings on the effects of haptics being incorporated in advertisements and cites a few companies that are further investigating and implementing the technologies.


This paper explains an experiment addressing the limited haptic feedback of laparoscopic tools and a proof of concept of haptic feedback laparoscopic graspers. The researchers found that those with haptic feedback were better able to perceive tissue boundaries.


This is the press-release-type overview of the specifications of a Pons device for neurostimulation.


This is a discussion of haptic integration in serious games. It provides guidance for integration and ways to implement haptics for the ultimate promotion of learning outcomes.

This is a popular culture discussion of using a tongue stimulation device to convey visual information as developed by Bach-y-Rita.


This wired.com article features the idea of haptics being used in flight simulators to enhance the virtual reality situations. It explains that a French company called Go Touch VR has designed and implemented systems to improve the immersive nature of flight simulators.


This study compared performance of inexperienced individuals learning dental techniques with a simulator. The subjects were separated into three groups that received visual device feedback only, instructor feedback only, or device and instructor feedback together. Those with instructor feedback performed better than those without, and feedback from both sources produced the best results. These results are not particularly useful as it is unclear whether haptic feedback was available for all sections. Otherwise, the comparison is between visual feedback and instructor feedback with ignorant trainees for whom visual feedback would provide no metric of appropriate skill demonstration because they would not know the desired output. This limits the conclusions that may be drawn from this study.


This paper studied the forces of fingers upon phone screens and the diversity of actions that users exhibit while using their phones. The paper’s aim was to understand the potential risks and injuries from the ways in which people use their phones, and contributed a wider understanding of the complexity of finger movement.


This was a study of haptic stimulation compared to non-haptic meditation examining ECGs. They found that haptics appear more effective at reducing stress.
This is an info page about morphing controls on car environment control systems. Morphing controls are those which change based upon what controls are desired or needed. In this example, they relate to car audio and temperature settings, but could be expanded to many fields.


This is an introduction to the methods and theory of visual substitution by Bach-y-Rita.


Vision and vestibular substitution are discussed by Bach-y-rita in techniques and tools for replacing lost or disabled senses and considerations of the Brain Machine Interface.


This paper provides a robust overview of haptics and haptic uses in education settings including background on haptics, implementations in classrooms, and learning outcomes. It provides recommendations for future development as well.


This study focused on the application of online mindfulness training in reducing stimulus-independent thought, or mind wandering, indicating short online training can have an effect on mind wandering - decreasing the frequency at which it occurs. The study focused on two online applications, Headspace and Lumosity. They found a stronger influence on mind wandering related to time spent on the app in the Headspace, and they did not see a significant change for those training with Lumosity, indicating that mindfulness training methods may significantly impact outcomes.


This study involving the tactile exploration of a 3-dimensional necker cube examined both the reduction of visual illusions when tactile feedback is presented and the mental response to the introduction of new information including the onset of mental response being influenced by the senses.

This is a proof of concept analysis of a finger sensitivity device for children with cerebral palsy. After two weeks of training, five of the seven participants saw significant improvement.

Daniel Blustein, Adam Wilson, and Jon Sensinger. Assessing the quality of supplementary sensory feedback using a crossmodal congruency task. *bioRxiv*, [https://www.biorxiv.org/content/10.1101/194977v1.full](https://www.biorxiv.org/content/10.1101/194977v1.full).

This paper investigated the ability to distinguish different haptic vibrotactile stimulation on a user’s body. Specifically, it examined how spacing of the haptic interfaces lent to differentiating the haptic signals and how that spacing had to be wider on different parts of the body to successfully perceive them as separate stimulators.


This research presents five different motor rehabilitation exercises in a post-stroke population with haptics, showing positive results.


This is a summary of haptics for breathing therapy, meditation, and mindfulness. It compared haptic, auditory, and haptic-auditory breathing guidance, finding haptic feedback alone most improved relaxation, but stress and difficulty were least improved. Audio-haptic least improved relaxation, but saw the greatest improvement in stress and task difficulty rating.


A meta-analysis of different modes of sensory feedback. It was found that visual-auditory feedback was most useful in single tasks, while visual-tactile feedback was most effective in multi-task environments and high workload conditions.
This study examined the importance of haptic feedback for perception of a virtual home button on smartphones. Vibration frequency and amplitude had positive perceptions, but perceived intensity was negatively related to users’ perceptions of the tactile experience. It may be viewed online at https://www.researchgate.net/publication/334365045_The_Vibrotactile_Experience_of_the_HOME_Button_on_Smartphones. 

This paper investigates how quickly body schema can change when first using a tool. Particularly investigating the ramifications of extending subject’s arms with mechanical grabbers, researchers found that only a small amount of tool usage can adjust the body schema during and after tool usage.

This paper examines the key features of the cortical homunculus, including its discovery by Wilder Penfield, who published work on the subject in 1937 after isolating the region during neurosurgeries of 126 patients.

This paper reviews the state of haptics in medical fields, discussing the training improvements with haptic simulators in different surgical fields, positive results in rehabilitation and more. It is more an overall survey of the field of haptics than of the benefits specifically.

This is a pilot test of a VR-based pinch simulator for long-term stroke rehabilitation. Positive effects were observed in the two pilot study participants and proof of concept usability and design was established with 30 able-bodied participants.

This paper is particularly meaningful in its examples of real-world applications of haptics that are available or under development. It furthermore examines the technical specifications and details of haptic expression including space and...
frequency discrimination in order to better understand the design needs of a haptic module.


This study of a myoelectric prosthetic investigated the applicability and success of a prosthetic with integrated haptic feedback. The prosthetic devices were equipped with a Desc-glove that provided sensory feedback based on the initiation and loss of contact with the prosthetic fingertips. Study participants completed a virtual egg task with increased success when haptic feedback was provided.


In this paper, two studies were conducted with different numbers of contributing sensory feedbacks. Study 1 shows that more feedback can improve performance, and study 2 shows the potential of overwhelming participants via decreased performance with more feedback.


This is a developers page reviewing the iPhone taptic interface and recommendations for development methods and considerations.


This paper discusses the principles and outcomes of neuroplasticity experiments with a particular focus on the physical neural changes. It dives deeply into neurological disorders and their occurrence or improvement because of plasticity. Much of the paper focuses on these topics, unrelated to haptics and neural plasticity, but there is a segment on motion therapy and aerobic exercise for promoting neural plasticity which may parallel with haptic encouragement of motion.
This long-term study of prosthetics use at home with haptic feedback upper limb prosthetics investigated usage information, psychological information, skill, usability, and more over the course of 115 days. The results of incorporating sensory feedback indicated a reorganization of participants’ body schema and contribution to a process of learning more similar to learned usage of intact limbs.

This technological review presents the past, present, and possible future states of haptics research and presents best practices for haptic device design and development to best provide meaningful touch sensations.

This large scale investigation of wearable haptics examines the usage of haptic devices for subjects with varying degrees of sensory limitation - from full loss (as with amputees), to no loss (as with fully-abled individuals using haptics for training purposes). Results indicate positive outcomes in diverse fields, and recommendations are made for the future directions of this research including multi-sensory applications and biomedical improvements for wider deployment of haptic technologies.

This study explored haptic computer applications and their ability to improve education for blind middle school students. The tested several of the applications with different middle school classes and got feedback from the students. In addition to finding more autonomy and the ability to work alone, students found the applications fun and engaging, and were able to develop better conceptual models of the topics. The paper also includes a list of 20 different applications that have been developed for grade school students to more completely interact with STEM concepts through haptic computer simulations.

This study investigated the use of haptic feedback upper limb prosthetics in reducing phantom limb pain, finding that feedback on grip strength on objects does contribute to a significant reduction of phantom limb pain and is therefore a promising technique for both increased functionality and pain reduction.


This is Norman Doidge’s earlier work on neurobiology (followed by *The Brain’s Way of Healing* [39]). It discusses Bach-y-Rita’s history and work in more depth than other source, and is also available in pdf format online at [https://www.brainmaster.com/software/pubs/brain/contrib/The%20Brain%20That%20Changes%20Itself.pdf](https://www.brainmaster.com/software/pubs/brain/contrib/The%20Brain%20That%20Changes%20Itself.pdf).


This book reviews many methods and mysteries of the brain and its healing process - a good read for research or pleasure. Most relatedly to this thesis, it discusses neural reprojection of lost limbs in monkeys with amputated fingers, and the PoNS device for balance and motor function therapy.


This online book and especially study metric displays the findings of students with different learning modalities - namely visual, auditory, and haptic. It is important to note that in this three-grouped study, haptic refers more to experiential and kinesthetic than artificial haptic feedback technologies. It may be viewed online at [thelearningweb.net/chapter03/page131.html](http://thelearningweb.net/chapter03/page131.html).


This paper examines haptic intervention in patients with Traumatic Brain Injury, or TBI. Initial results indicate that haptic nudges to stimulate attention were effective in target acquisition.


This paper describes a haptic technology for learning to write letters using a computer program with three settings and five languages to encourage efficient and characteristic handwriting of letters. The addition of haptic technology shows measurable improvement in the study population of kindergarteners who received haptic support through the learning application.

This web article describes some of the really novel emerging consumer technologies that involve haptics including a Kindle that simulates pages turning and the texture of paper, and the Apple Watch that uses Apple’s Taptics Engine to simulate scrolling through menus.


This investigation of biological blood flow data in a heart extends beyond 3D representations of a beating heart into flow line analysis to better examine irregular flows.


This is a study of wrist positioning of able-bodied participants to examine the applicability of different haptic force mechanisms for prosthetic devices. The study showed how relatively few devices may provide rich tactile feedback.

[46] David C Van Essen. Organization of visual areas in macaque and human cerebral cortex. [https://www.cns.nyu.edu/csh/csh04/Articles/Vanessen-03.pdf](https://www.cns.nyu.edu/csh/csh04/Articles/Vanessen-03.pdf).

A quantitative investigation of how much of the cerebral cortex is dedicated to different senses. It is a very well-written investigation with helpful images and diagrams. They studied the dedication of the cerebral cortex to different senses in Macaque Monkeys and Humans.


This paper examines sensory illusions for reducing the phantom limb pain of amputees. A Mirror Visual Feedback system was then developed to provide visual and haptic illusions to reduce phantom limb pain. Success metrics varied across amputation sites, but overall, there was a strong indication that further pursuit of haptic supplements to create a multisensory environment for Mirror Virtual Feedback can improve outcomes.

This study examines methods to reduce visual overload in a cockpit and explores whether haptics may be used to replace some elements of the controls and system information on a flight deck in order to reduce the notification fatigue of a pilot’s visual field. It presents data on including haptics in control mechanisms.


This study investigated the close relationship between motivation and learning outcomes, and how haptics may improve student motivation and engagement.


This is a popular culture review of smartphone apps for breathing, meditation, and mindfulness.


This study of vibrotactile haptics applied directly to amputated limb stumps showed a reduction in phantom limb pain and an improvement in sensory acuity and spatial discrimination upon the stump after training with the haptic mechanisms. It also demonstrated the ability to create illusions of the amputated limb based on varying the vibrotactile stimulator locations.


This article provides examples of how visual info could be represented tactically. It presents helpful figures and details the ways in which different features could be conveyed to blind users.


This examination compares visual and force feedback in piercing a tissue boundary. The results indicate that visual feedback alone is better than haptics alone, likely because of a delayed motor response. Haptics become particularly useful in large force situations and when visual feedback is degraded or unreliable.

This paper presents the opportunity for using haptics to simulate flight simulation apparatus and instrumentation in VR applications. It also discusses dynamism of simulators to imitate built equipment on different aircraft. It provides a conceptual model for a haptic interface using ultrasonic haptics and motion tracking to present a method for flight simulation.


This quantitative study examined smartphone haptics for several tasks, finding that in activities in which the visual field is small or disrupted, as with drag-and-drop tasks because of the finger’s motion through the line of site, haptic feedback improved accuracy and speed. With tapping tasks, haptics did not exhibit significant change. In path-following tasks, haptics improved accuracy, but not speed.


This article contains more information about the resource dedication of the brain to different senses, investigating the neuronal firing rates rather than the area or volume of each sense’s resources. It does not include citations, so its validity is unconfirmed and it seems to echo much of the information I read about R.S. Fixot’s study [125] but which the original study does not reference.


This thesis work is an investigation of haptic interfaces to supplement and improve safety while driving. It primarily investigates ”secondary” controls such as audio system controls. Very usefully, it cites studies investigating multi-sensory feedback and the balancing of visual, auditory, and haptic feedback. It cites several studies which I then pursued directly including one by Cockburn and Brewster regarding sensory overload [30].


This study from Johns Hopkins examines haptic technology deployment with grade school students, undergraduate, and graduate students especially in robotics.

This textbook, available through Swarthmore’s library exchange, includes numerous articles by different authors regarding the history and opportunities of haptic research. This provides an accessible overview of information on haptics with significant specificity within each included article.


This study investigated experienced surgeons using haptic-enabled training devices. Survey responses indicated a lack of realism, but performance showed less tissue stretching in those who had haptic feedback.


This is a discussion of haptics used in different fields of education including Chemistry, Biology, Engineering, and more. It also provides valuable examples of the use cases of haptics in education.

[62] Jun Hu, Loe Feijs, Mathias Funk, and Bin Yu. Breathe with touch: A tactile interface for breathing assistance system. [https://hal.inria.fr/hal-01609385/document](https://hal.inria.fr/hal-01609385/document).

Using breathing for relaxation and regulation, a shape-changing airbag was used to deliver tactile breathing guidance to users. Surveys were completed to compare to visual and auditory breathing assistive systems. SDNN (Standard deviation metric for heart rate variability) increased after testing with haptics (higher SDNN indicates better heart health), and respiration rate decreased.


This piece focuses on the topic of echolocation and the possibility of developing echolocation skills as a human. It features Daniel Kish, a blind person who uses echolocation to move about the world in much the same way as sighted people do. However, in echolocation, Kish uses only the feedback of sound to detect his surroundings.


This review of studies of the senses examines the distribution of information for different senses and why such a distribution occurs. Specifically, research of the visual sense is far more studied than any other. This, Hutmacher argues, is due to a societal bias toward vision, which resulted in the development of better tools for studying vision that self-enforce further study of vision over other senses.
A "Fact or Fiction"-style piece discussing various statistics online relating to the devotion of brain processing to vision. Again, cites R.S. Fixot [125] for 2-3 billion neuron firings per second and 2/3 of those dedicated to visual processing.

In this study, participants were surveyed and tested on their outcomes of playing serious games. This was not a study of haptics, but showed quantitatively that enjoyment of the game had a significant impact on learning motivation. Enjoyment of the games did not, however, have a significant effect on learning outcomes themselves.

This study of virtual reality considers the addition of passive objects to the virtual reality environment by adding simple objects to the real physical environment. In the study, simple objects made of plywood and styrofoam were used to contribute to a more immersive perceptual experience in the virtual reality.

This research reviews the existing body of research for haptic applications of accessibility to include people with disabilities. It highlights the very small quantity of research that exists and the small area of focus of disability research in the contexts of computer accessibility, wheelchair and robotic control, and rehabilitation.
This is a discussion of a novel portable visual display for deaf patients.


In this study of elementary school physics instruction, many modes of learning were used to create a more immersive computer simulation of four physics phenomena: gravity, magnetic force, frictional force, and viscosity. The tools were developed for users with visual impairments, but also enhance learning for all students through multimodal feedback, engagement and interest, and increased complexity.


This study is atypical, but demonstrative. It examines breathing exercises in healthy individuals for possible rehab and recovery extensions. Feedback was given to indicate exercise performance, and the study found significant improvement using haptics vs. not. This study expressly examined haptic effects on therapy success, not the effects of therapy itself.


This is a study investigating a Phantom device and an Impulse Engine Device to render textured surfaces and 3D shapes for blind users.


This article, based on Amisha Jha’s research, discusses findings of the incidence and ramifications of a wandering mind. It was found that our minds wander about 50% of the time, and context is given for the ramifications that could have in various high-importance jobs and instances.

This paper is not particularly useful in the study of haptics, but examines the cross-modal intersection of auditory and visual senses and how the two interact and can distort perception of the other. This lends toward a discussion of illusions and sensory overlap when senses are no reliable.


This study investigated eight classes of middle and high school students studying viruses and biology. All students developed improved models and conceptualization of the viruses. The half of the students who received haptic feedback simulations had significantly greater interest, engagement, and motivation toward the topics, indicating that whether or not learning is improved, motivation and attitude can be improved through haptics.


This study presents different tasks of varying challenge levels for subjects to understand how the mind wanders when demands upon it change. The researchers found that the more concentrated a person reported being, the less their minds wandered. However, in subjects with less Working Memory Capacity, the more challenge or effort a task required, the more their minds wandered. Interestingly, many participants were not surprised by their frequency of mind wandering and even said it was purposeful.


This book discusses neuroscience anomalies through stories and the brain functions and representations behind them. An enjoyable read, it has a section on Paul Bach-y-Rita’s sensory substitution, which was instrumental in expanding the scope of this paper to sensory substitution.


This research surveyed participants on the incidence of mind wandering, finding that at 46.9% of the sample points, people reported their minds having wandered. In this study, they also surveyed happiness, finding that mind wandering to happy thoughts did not have a positive effect on overall happiness, and mind wandering to neutral or sad thoughts had a negative effect overall. Interestingly, very little mind wandering was reported during sex.

This is a research paper presenting the usability and skill of typing on a flat keyboard given varied haptic and auditory feedback. It was found that intensity of haptic feedback has a impacts typing efficiency and error, while auditory intensity does not.

[81] Eric Klinger and W. Miles Cox. Dimensions of thought flow in everyday life. *Imagination, Cognition and Personality, 7*(2):105–128, [https://journals.sagepub.com/doi/10.2190/7K24-G343-MTQW-115V#articleCitationDownloadContainer](https://journals.sagepub.com/doi/10.2190/7K24-G343-MTQW-115V#articleCitationDownloadContainer).

This 1987 paper describes the results of a study on mind wandering, stimulus-directed, and dream-like thought. They found that the mind wanders 1/3 of the time, is stimulus-undirected another 1/3 of the time, and contains dreamlike elements another 1/4 of the time.


This paper discusses the barriers and deterrents to prosthetic usage in upper limb amputees with an in-depth investigation of prosthetic users in England.


This paper discusses numerous methodologies to distort haptic perception, that is, create illusions. Of particular discussion were illusions regarding weight and how size, shape, texture, and even temperature can affect an object’s perceived weight. Distance and motion relative to the body is also discussed. Finally, the authors included a section on further considerations such as touch modes and mixed media interactions.


This is an expansive overview and discussion of haptics and qualitative reporting of sensitivity, applicability, malleability, and sensory interactions. It begins with how touch is perceived and then discusses the ”what” and ”where” neural pathways extensively. It closes with a discussion of vision-touch interactions and neuroplasticity.

This paper explores methods and opportunities for creating haptic interfaces for visually impaired users. It examines and demonstrates different implementation methods with example images representing the haptically interactive graphs, plots, and figures opportunities presented. It also discusses opportunities for using things like texture to create a fourth dimension of comprehension to convey additional information such as different data groupings.


This describes Lemire’s LIMI (Learning and Interpreting Modality Instrument) process and the three classifications it employs: visual, auditory, and haptic. This tool is used by others in the field to identify learning styles, and this paper also explores a comparison of other tools and study results yielded by using this tool.


This paper argues that human body schema plasticity is a critically complex issue in tool usage. It is influenced by tool use frequency and duration, type of usage, and visual aspects of the tools. Humans demonstrate near-instant plasticity in body extension with tools, but additional environmental attention changes are observed with more extended tool usage. For more complex tools that perform tasks a human body cannot (i.e. dangerous activities like reaching into fire), a more robust understanding of tool and body schema extension must be understood - the understanding of is predicted to be distinct from other animal tool usage. Prosthetic considerations are also discussed relative to aesthetic and physical adaptation.


This is a paper comparing Microsoft keyboards with and without haptic feedback on the metrics of speed (words per minute), keystrokes per character, and error rates. The keyboard was one of the Surface tablet keyboards without depressable buttons and they tested no haptic feedback, local haptic feedback wherein only the finger pressing the key receives a peizo-electric vibration, partial haptic feedback in which the entire typing hand receives feedback under all five fingers, and global haptic feedback delivered to all 10 fingers. All of these were also studied with no auditory feedback and with an auditory click. The study revealed a statistically significant increase in speed and decrease in error rate with haptic
feedback of any kind (compared to no haptics). There was no statistical variation in keystroke length.


This paper outlines best practices for device development of visual displays for conveying sound information. It then presents two technologies developed for deaf people to receive information about non-speech sounds.


This is a Johns Hopkins University Medicine overview of the regions of the brain focusing on the cerebrum and the lobes therein referencing which senses are processed where.


This is the marketing page of vOICe soundscape technology - a method of converting views to sound input for blind people.


This is a very large literature review of haptic assistance technologies for driving. It explains different technologies available and the studies done on collision avoidance, attention maintenance, and lane drifting alerts, and far more.


This paper discusses the responses of individuals with ASDs to tactile stimulation. It touches on haptic research with much the same findings as other generalized studies - the heteronormativity of ASDs makes the study of any single intervention or observation more difficult in its inconsistency of expression and reaction.


This very wide and comprehensive review of work explores the development of haptic sensitivity with age, haptic and visual perception comparisons, and studies of applications of haptics in various fields of science education. It presents studies finding a positive haptic impact and those that remain inconclusive. Overall, the authors conclude the benefits of haptics for education are still not understood
and there remain significant barriers to implementation in education. This review investigates works prior to its publication in 2006 and may be a good model for a follow-up review of more recent works.


This is a presentation by engineers at Apple on the use of the Apple taptic device, which uses super-low frequency sound to produce haptic vibration stimulation.


This paper explains the development and background of 20 computer applications targeted at blind student populations to provide more robust haptic sensory input to replace visual input most often used in STEM computer applications. It also examines quantitative results of pre and post-testing with students who also especially enjoyed the use of haptics. This research and development was published following Marjorie Darrah’s article examining some of these apps in 2013 [36].


This study provides consideration to how haptic device usage accuracy is tested and the metrics used for defining device accuracy. It more closely discusses and tests device ”transparency” or accuracy for teleoperated surgery. Where previous studies consider only the machine accuracy, this study examines the human user success as a combined system with the teleoperation machinery.


This is a comparison of altitude maintenance using tactile feedback in 4 cases - no visual feedback, altimeter-only visual feedback, vertical speed-only visual feedback, and full altimeter and vertical speed visual feedback. As one would expect, tactile and full visual cues showed the best performance, but altitude maintenance was achieved without visual cues at all as well.

This is the Oxford English Dictionary entry for the word haptic. It is useful in providing a baseline for defining haptics. The first definition is: "Of the nature of, involving, or relating to the sense of touch, the perception of position and motion (proprioception), and other tactile and kinaesthetic sensations."


This is an overview of brain regions and is useful in more fully understanding the regions involved in sensory processing.


This is an informational website page about the effects of traumatic brain injury.


This paper presents the exploration of a device for haptic stimulation using magnetic actuators.


This overview discusses key findings in haptics research related to surgical skill learning. These reviews highlight adjustments and exaggerations of haptic feedback used to improve performance and reference papers pertinent for further examination.


This study experimentally compares pilot performance in normal conditions, with haptic force feedback, and with study-designed automated controls. The best performance was with automation, but haptic performance also demonstrated improvement over normal visual-only conditions.


This review dives into the array of implementations and integration of haptics in video gaming. It investigates the history of video games, the industry as a whole, haptic devices such as joysticks and steering wheels, and opportunities for "serious" games for training such as in medicine and education. It also discusses haptic opportunities in education, healthcare, and more. Finally, it also touches on accessibility for blind users.

This quantitative study of 42 kindergarten students investigated acquisition of handwriting skills with a haptic interface. The haptic test group was significantly faster, had more consistent speed, and had fewer breaks in writing after training with the haptic interface.


This literature review presents the different methods and areas in which haptics may be used for data visualization and perception for people with visual impairments.


This is an editorial overview of haptic media studies serving as the introduction to eight selected pieces on haptic innovation. It introduces the state and direction of haptic studies which have recently occupied a more significant sector of sensory and interactive studies. The paper and collection presented are shared with the hope to unite the community of researchers on haptic media studies and present guidance for entering this previously underresearched space.


This paper likens the current concerns about haptics to historical worries about physical buttons. Some arguments about the advancement of haptics include the idea that users lose their relationship with the physical world and that usability will be negatively impacted. Plotnik explores how similar these arguments are to those waged over the past 100 years as physical buttons were developed.


This research by Tim Pons and Edward Taub investigates the cortical reorganization of sensation in macaque monkeys, also known as Taub’s Silver Spring Monkeys, which had limbs that had been surgically deafferented so that touch sensation was not conveyed to the monkey’s brains. This research presented the
ide that the cortex reorganizes more extensively than previously found in order to account for lost sensory feedback and redistribute or rededicate resources to remaining sensory pathway.


This paper examines the structures and systems that contribute to highly specified textural information perceived by the fingers. Specifically, it examines how the ridges of fingertips contribute to sensing vibration elicited by different types of surfaces.


This is a paper investigating how EMG (electromyogram) signals can be used to control prosthetic devices.


This study examines statistics of prosthetic type and usage divided by upper and lower limb prosthetic users. It includes tables with high degrees of details regarding factors of prosthetic design, prosthetic use, amputation location, amputee engagement, and more.


This article describes the construction and application of a mirror box to give the illusion of intact limbs to amputees. This illusion was able to reduce phantom limb pain for participants, and even cause the complete loss of their phantom limbs in some cases.


This study of college and university students examines how haptics may supplement the understanding of anatomy through a 2-dimensional drawing exercise of anatomical concepts with informative haptics, finding that haptics improves retention and understanding.
This research interrogates the reasons for upper limb prosthetic rejection or lowered rates of use. It compares the technologies available and the primary limitations users face when using even highly advanced prosthetics.

This is Rose Ridder’s engineering senior design project developing an EMG-controlled prosthetic with vibrotactile haptic feedback. Access granted by the Swarthmore College Thesis Archives. Video available at https://www.youtube.com/watch?v=qKtCjis2ZZE

This article reports the frequency of haptic and data visualization publications over time presenting timelines and historic reviews of the progress made in the field.

This examination of haptics classifies active haptics as those in which the user is control of their movement, whereas passive haptics are those in which the device controls the user’s motion, making the user a passive follower. The study found that active haptics (in which the user controls motion and exploration) contribute to better success in perceiving surfaces. Distinguishing shapes, such as squares, circles, and triangles, was significantly improved when the user was responsible for actions. Passive haptics (in which the device controls motion) contributes to a better conception of motion pathways.

This study examined how haptics may be used to provide an illusion of 3-dimensional buttons on a touchscreen and how the illusions of size, depth, and other characteristics could be altered.

This study details the development and outcomes of a virtual reality simulated reaching task. Wearing a VR headset, upper limb amputees reached toward an object and saw the illusion of two intact limbs reaching toward the object. Haptic feedback on the intact limb resulted in a significant decrease in deafferentation (or phantom limb) pain.


This study, referenced by Minogue and Jones [91], indicates choice of manipulation is the key to attentiveness in learning.


This dissertation presents the results of numerous studies conducted by the author for different activities and skill acquisition with and without haptics. The author’s use of the word “Passive” diverges from our operating definition, but the studies and recommendations are nonetheless quite useful guidance and ideas for applications of haptics in training and rehabilitation.


This study is misquoted all over the internet as saying ”50% of the neural tissue is devoted to vision and almost two-thirds of the electrical activity of the brain is devoted to vision when the eyes are open.” ([https://psychology.stackexchange.com/questions/19190/proportion-of-cortex-dedicated-for-vision-and-hearing](https://psychology.stackexchange.com/questions/19190/proportion-of-cortex-dedicated-for-vision-and-hearing)). However, the paper doesn’t mention overall brain anatomy, percentage dedication, or otherwise. It is discussing visual training methodologies and outcomes only.


This study examined the outcomes for 21 Traumatic Brain Injury patients with half the group participating in visual and haptic virtual reality training for two weeks versus a control group in standard attention training. Those in the test
group showed significant improvement over their control counterparts and retained attention learning from day to day - even for those suffering from sustaining amnesia.

This chapter discusses wide themes of tactile experience. Section 5.2, which is accessible open-source within a grouping of related articles at https://www.sciencedirect.com/topics/medicine-and-dentistry/skin-sensation discusses specifically the classifications of skin sensations by depth and sensation type. Other sections also provide useful figures and descriptions of other sensory-related topics including Wilder Penfield’s homunculus cartoons.

This paper discusses the importance of touch-feedback in dental surgery and the lack of training that medical students receive in this area. Tests of a haptic device for training of endodontic surgery indicate force feedback show improved outcomes.

This paper details the development and clinical results of a 10-child study of children with learning disabilities in a game-type haptic learning interface. Especial consideration was taken with balancing the fun of the tool with the educational component, and the engagement and attentiveness of the participants.

This is a how-to page for setting the haptic intensity and occurrence on your Android Phone.

This is a how-to page for setting the haptic intensity and occurrence on your iPhone.

This thesis study investigates kinesthetic learners and accommodations made by professors in undergraduate classrooms, using the LIMI test developed by Lemire.


This paper describes the hardware and software of a haptic dental simulator and the design considerations and potential implementations.


This is a radio podcast presentation of the concept of average and body average. One segment discusses the World War 2 surge in pilot deaths due to cockpit immobility and the assumption that pilots’ bodies adhered to the measured human average. When cockpits were made more adjustable, flight operator success improved.


This study investigated physical performance after stroke rehabilitation with haptic feedback. Unlike other studies, this one also measured fMRI data and showed that those with haptic feedback exhibited better cortical activation than those who had no haptic feedback.


This study compares unimodal, bimodal, and trimodal feedback for visual, auditory, and haptic feedback. The researchers found that with visual, haptic, and visuo-haptic feedback, performance improved (with haptics only performing best, and haptico-visual second). For feedback with audition involved, performance decreased, indicating both that it is not as beneficial alone or with one other feedback system, but also the potential for overwhelming the senses.

This exploration of haptic interventions discusses how attention may be impacted. Much of the work centers around short-term attention improvements sustained after haptic rehabilitation, but some work also explores the neural impacts of the strategies.


This popular culture news piece on haptics explores what different companies are doing in the tactile feedback space and notes the audience perceptions and engagement improvement in response to the addition of haptics in advertisements.


This overview of Minimally Invasive Surgery includes studies from 1985-2008. It discusses the promise but rareness of haptics and recommends further research.


This paper investigates the neural ramifications of amputation and the barriers to successful rehabilitation. They pay particular attention to the timing of sensory and neural changes following a traumatic amputation and make recommendations on how to best accommodate these changes for maximum rehabilitation success.


This study presents haptic additions to science modules studied by elementary school students. In the signature application developed in this study, simple machines with haptic interface improvements were explored to promote a better understanding of physics.


This textbook provides an overview of sensory perception, neural pathways, and other background information for the study of haptics. Chapter 13 on touch was most directly associated with haptics and neural perception of the sense of touch.

This is an overview of neural plasticity and the different sensory substitutions that may be available. It is the work of Bach-y-Rita who continued to develop devices to accomplish varying substitution techniques.


This is another overview of Bach-y-Rita’s work and considerations of sensory substitution.


This is a design discussion of the original visual-haptic conversion chair made with a 20x20 vibrating array on a dental chair. This device was developed for blind users to "see" their environment, and the success of this technology was later developed by Bach-y-Rita into a more manageable and portable tongue stimulation device similar to the PoNS device.


This research investigates Virtual Reality, game-like stroke rehabilitation with haptic feedback embedded in the VR.


This study examines how anatomy may be better learned with the addition of 3-dimensional haptic models and manipulation.


This study investigated the ideal frequency of vibrotactile feedback from phones. They found the ideal frequency was greater than 180 Hz, greater than that from previous studies.

This is a study of attention in Traumatic Brain Injury patients and how a 15Hz sine wave haptic rhythm applied to the hand can contribute to significant improvements.


This research investigated performance of surgeons across skill levels in a transfer-and-place task using one simulator with haptic feedback and one without. Subjects were placed under cognitive load conditions by doing mental math. It was found that having haptic feedback increased speed and accuracy significantly both with and without a cognitive load. Without haptics, no cognitive load was faster, but not more accurate. The increased speed effect with haptics was exaggerated with experienced surgeons, perhaps because they had spare cognitive resources to devote to the feedback.


This paper compares long-term training performance with haptic feedback and without. It was found that learners with haptic feedback performed faster and more accurately during initial training but reached a learning plateau earlier. Over extended training periods, performance of laparoscopic surgery was comparable between subject groups, suggesting that haptic feedback implementation for this training may not produce significant enhancements for training over time.


This news article explores why humans evolutionarily developed fingerprints and the purposes they serve.


This paper investigates the body of research and development of sensory substitution technologies for blind users. It includes auditory and haptic substitutions and discusses the critical need for training on any new substitution system as well as the complex design considerations for sensory perception. The authors discuss the risk of overstimulation and sensory overload, as well as ways to focus the sensory feedback in the most conducive ways.