James Barabas – Written PhD General Exam – Sensory Substitution
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1. Sensory substitution research has had a reasonably long history. What, in your opinion, are some of the primary success stories (practically useful systems, and key theoretical insights) from this field so far? If the list of successes is modest, discuss the scientific and practical challenges that have limited progress.

The primary successes in the field of sensory substitution have, with few exceptions, been ones that do not seek to entirely replace a lost sensory system, but instead make more modest attempt to replace that system for only a specific task. This is especially true when the impaired sensory system is vision or audition. The uses of these sensory systems are so diverse that no single compensatory strategy effectively replaces all uses of the impaired system.

One major success was the replacement of raised type resembling roman characters with the raised dots used in Braille. Although many aspects of reading Braille resemble the task of reading print (recognizing a sequence of spatial symbols laid out in lines on a flat surface), tactile perception seems to be better suited to recognizing more localized and high-frequency patterns. While early raised type alone did allow many visually impaired people to access written material, the transition to Braille appears to have been a critical refinement that helped foster widespread adoption.

Although other systems for mapping arbitrary visual patterns to touch have been developed, success with these devices has been more modest. These systems include the Optophone, a light to sound conversion system demonstrated in 1912, The Optacon, a fingertip vibrator array linked to a handheld camera, commercially available from the ‘70s through the ‘90s, and the briainport tongue vision system in currently in testing. With these tools, some individuals have reported dramatic successes, but adoption has never been widespread. Reasons for this may have been the expense and lack of portability of these devices. Since these devices only provide a small fraction of the information bandwidth of normal vision, it is also likely that users moved to collections of other tools that proved better suited for specific tasks (eg. Scanners with speech synthesis for reading, using a guide dog or cane for environmental awareness.)

Other successful uses of one sense to compensate for the loss of another include uses of spoken language as a proxy for visual experience. Screen reading technology, where text, and even layout of windows on a computer screen are read and described by a synthesized voice, has gained widespread adoption among the visually impaired. Although slower and potentially less rich than visual experience, screen reading can functionally replace vision for many computer tasks.

Notable success has been reported with vestibular prosthetics (mapping the user’s head orientation to tongue stimulation). In this substitution scheme, the vestibular signal is a time-varying two-dimensional measurement with bounded range. This measurement is “displayed” as a single point of stimulation on the tongue that changes position to indicate head tilt. With this device, users are able to completely recover lost abilities. The success of this scheme is due in part to the relative simplicity of the lost vestibular signal compared to the sensory bandwidth of the tongue. The choice of mapping two spatial dimensions of acceleration onto two spatial dimensions of tongue surface may also help in the task of learning this mapping.

Over all, it seems that the successful sensory substitution schemes have been ones that exploit inexpensive or commodity tools to help replace a sensory system for one specific task. Performing a single task well seems to lead to wider adoption than attempting to do many things poorly.

2. Imagine that you have been charged with developing a sensory substitution device to help the blind navigate. Specifically, let us say that the task of the system is to serve as a guide to a blind newcomer to Cambridge. The system has to be able to help the user find places, walk down streets and also avoid obstacles. Briefly outline your design for such a sensory substitution device.

Several research and commercial navigation aids already exist for helping the blind navigate in an urban setting. These devices usually use GPS to determine the location of the user, and provide Braille, tactile, or auditory cues to assist the user with navigating the environment. While it seems that several of these devices address the high-level navigation task of orienting and directing the user, none of the commercially available devices appear to help with mobility challenges faced by the blind. These unaddressed challenges — ones that are traditionally met by using a cane, or a guide dog — include finding a clear path for walking, detecting distant moving obstacles (dog only), and alerting the user to steps or other changes in the walking surface. These needs have been considered by research efforts using sonar, optical ranging and video sensing, but do not appear to have been successful enough for commercialization.

Design of a mobility device requires a compromise between attempting to build a complex system to perform the task in the best possible way (perhaps the way a sighted guide might walk with the person, answering questions, watching for hazards and directing their travel, all at a very high level), or making a more realistic device that a person would be able to afford, and could rely on, but might incorporate less intelligence.

I will describe my design in three parts: 1) physical interface, 2) High level navigation assistance and 3) Mobility assistance

The physical device would be in the form of a “fanny pack” (worn around the waist with bag in front) a handheld contoured controller that sat in contact with much of the user’s skin when held, and a set of headphones.

The fanny pack would contain a laser rangefinder and a gps-enabled smartphone. The surface of the handheld controller would contain an array of microfluidic tactile actuators for presentation of Braille to the fingertips, but also spatially-mapped texture covering the whole hand for presenting information about the environment.

Auditory cues seem to be a natural choice for navigation, as most blind and sighted people already use environmental audio cues for localizing objects. One drawback to using synthetic sound in a navigation aid is that it has the potential to mask natural sounds that could also be valuable for obstacle avoidance or orientation (such as the sounds of cars or other pedestrians). A reasonable compromise would be restricting the duration and volume of sound cues so as not to compete with environmental sound. Additionally, open-ear headphones would allow the use of binaural positional audio for indicating the direction of a destination, while only minimally interfering with natural hearing when the system was silent. I would propose an automatic volume control system for the device, adapting to ambient sound levels, and would provide instead of a traditional volume control, a knob that allowed the user to tune the amount of guidance given by the device. Turning the knob up would produce continuous verbal guidance, turning it down would produce sound only in emergencies.

For helping the user find a previously unvisited address I would use a GPS system with compass, and map database similar to currently available blind navigation aids, but would also build a system for annotating routes so that users of the system could passively or actively give feedback about the busyness and level of maintenance of different streets. Route descriptions and other directions would be dictated to the user using speech synthesis. The user would be able to activate a compass-heading indicator by pressing a button on the controller. This heading indicator would play a periodic tone rendered with the spatial audio system to appear to originate from the north, or optionally the navigation destination.

To assist with the mobility aspects of navigation, the device would present information from the laser rangefinder as a tactile depth map on the handheld controller. To reduce latency, Information about obstacles would not be scanned for recognizable obstacles, but instead presented raw, or marginally pre-processed to the user. Pre-processing might include spatio-temporal high-pass filtering and/or median filtering, but efforts would be made to minimize latency.

Ultimately, the device would be developed further with the guidance of a panel of blind potential users.

3. Create a 'substitutability matrix' for the senses: For each of the five senses, consider how well each of the remaining four can serve as substitutes. What capabilities are substitutable and which ones might not be?

Information Sensed:	Sensory System Used				
	Visual	Auditory	Tactile	Olfactory	Gustatory
Visual	Eg. Magnification, rear-view mirrors.	General vision can be approximated at low spatial and temporal resolution using space to pitch mapping such as with the vOICe system. Some blind people successfully detect environmental objects using echolocation. Vision can also be approximately replaced (at lower bandwidth) by descriptions of the visual environment given by another person. This approach is used in Descriptive Video Service Specific visual tasks can be nearly fully replaced by auditory signals in: Text-to speech dictation, acoustic street signs.	Cane, Braille, Tongue/ skin vision (can be effective for simple tasks)	These sensory systems have very limited bandwidth. May be suitable for alerting a user to proximity a specific object, person, location, but not capable of general sight replacement. With training, a fairly large number of proxy smells/tastes could be assigned to specific events, but could only support a few events per minute. This would likely preclude the use of sequences of smells/tastes as codes for a larger vocabulary of events.	
Auditory	Successful for specific tasks: Closed Captioning, sign language, lip reading. Spectrogram display could convey all sound information in realtime. Recognition of at least some sounds likely with practice.	Pitch re-mapping should be possible for overcoming local cochlear damage.	Existing attempts: Frequency-band skin vibrators (modest success)	As above, might be used to alert user to specific pre-selected sounds or words. Insufficient bandwidth for general sound replacement.	
Tactile	Used without assistive technology as primary, but incomplete replacement for tactile, vestibular impairment. Successes with visual feedback of forces on remote surgical instruments suggest that visual technology could provide improvements to innate ability to employ this substitution.	Suitable for specific interactive tasks requiring pressure/temperature monitoring at a single body location. Might also be suitable for replacing sensation on a single fingertip, but would face similar challenges to vOICe approach. Probably not suitable for full-body general tactile replacement as there are many separate body regions that would need to be mapped into a single tone space. A slower approach could use a code, such as speaking location and type of mechanical contact with body.	Touch (on tongue) has been effectively used to replace vestibular sense. Other translations of one tactile region/channel to another should be possible.	Likely too slow to be useful for most closed-loop tasks. Could be used for initial alert to injury or other simple detection events.	
Olfactory/ Gustatory	Handheld devices with visual feedback are already in use for detection of some chemicals. Might be difficult understand equivalent smell/taste of combinations of detected chemicals, but a computer could be trained to recognize and display name/picture of common association with	Functional replacement should be possible. Similar constraints to visual replacement.	Should be suitable. Could at the least be used with a code like Braille to represent detected chemicals.	Space of tastes smaller that that of smells. Might be possible to replace lost taste primaries with smells, but these systems might not easily be remapped as some chemical senses (eg pheromones) have lower-level and even	

	combinations of chemicals. Technological hurdles for continuous sensing spanning human-detectible chemicals			subconscious projections.

4. Critically analyze the following argument: In developing different sensory systems for a given organism, evolution has likely tried to maximize the orthogonality of the senses, i.e., each sense detects and analyzes a very different aspect of the environment. Such orthogonality would enable the organism to get much more information about the environment than if the senses were redundant. Given this orthogonality, sensory substitution efforts are fundamentally doomed to fail since they are premised on the existence of similarities across different senses.

The argument first suggests that because orthogonal senses would enable gathering of the most information, this would drive evolution to produce organisms with orthogonal senses. In reality, there are many other pressures driving evolution of senses, and the sensory systems that have evolved are not necessary orthogonal. For example, making multiple simultaneous measurements of the same variable can reduce measurement error, which could certainly have evolutionary benefits. Additionally, the cost of maintaining a genome large enough to produce truly orthogonal measurements might be higher than the benefit it would afford. Also, fitness of an organism that had overlapping senses might allow individuals greater ability to survive despite damage to one system. Human senses contain many overlaps in the variables they measure. For example, within the visual system, a single wavelength of light may activate both the rods, any of the three cone types (although with different probability). Between sensory systems, humans can measure the size of objects both visually and through tactile exploration. The ability to measure the same physical dimension with both senses allows for the use of either sense for some tasks (for example when one is occupied), but also enables the possibility of transfer of knowledge gained from one sense to be used by another.

The argument then suggests that if senses were orthogonal, there would be no similarities between them to exploit for sensory substitution. But orthogonally of two measurements does not require that they be dissimilar. Consider the case of dimensional measurements of a rectangle on a sheet of paper. Measurements of the height and width of the rectangle are orthogonal – a ruler used horizontally can measure the width of the rectangle, but can give no information about the height, and vice versa. Despite this orthogonally, both dimensions can be measured using the same ruler, simply rotating it to take each measurement. Additionally, rotating the page can interchange the two dimensions. These simple manipulations of the measuring apparatus, or the stimulus can allow one sensing device to substitute for an orthogonal one. Taking this example literally, people are able to perform mental rotations of objects, such as when playing Tetris, allowing the use of visual measurements of vertical extent of a puzzle piece to decide if it will fit in an available horizontal space. Although the transformation of an object between spatial dimensions may be easier to imagine than between a spatial and nonspatial dimension such as pitch, the different physical nature of these dimensions does not preclude there being common mechanisms within an organism for processing those measurements. In fact, different sensory “systems” do have processing techniques in common. For example, both vision and touch have systems of lateral inhibition for pre-processing inputs, and have two-dimensional cortical maps corresponding to two-dimensional sensing “surfaces.” Also, It is not surprising that overlapping mechanisms exist within different sensory systems, as ultimately new sensory capabilities evolve by small modifications to and crossing of existing genetic blueprints.

The argument above may highlight some of the challenges in developing sensory substitution systems, but is flawed. The existence of successful sensory substitution tools (such as the vestibular prosthetic) further shows that these systems are not all doomed to failure.