Neuroplasticity of Sensation and Perception

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Biological sensory mechanisms and the cognitive processing of their input are responsible for the creation of our subjective reality. While this has practical implications for survival and the advancement of our species, it also prompts a longstanding philosophical conundrum: do we experience a representative, true version of our existence? Research in psychology and the emerging landscape of biotechnology and computing pave the way for the beginnings of an answer, along with fine-tuned control over the future of human sensation and perception. Yet, even as we start to wield the tools to manipulate our umwelt, we cannot be sure of the consequences. The following literature review is meant to provide necessary context and serve as a list of considerations in safeguarding against the harmful advancement of technology.

First we must consider the limited processing capabilities of the brain, with which our sensory mechanisms must interface. Dual-coding theory (Anderson, J., 2015) describes knowledge representations as existing in one form, which can be translated into another if required. An example of this is translating a visual perception into verbal speech, which is processed through language structures such as Broca's and Wernicke's area (Anderson, J., 2005). An alternative way of looking at knowledge representations is as an amodal symbol system, where information regarding perception could be translated into a universal code, from which other representations of the same information can be drawn. Put another way, the amodal symbol system refers to representation abstracted from its original form. As Lawrence W. Barsalou explained in his 1999 review, "following the cognitive revolution in the mid-twentieth century, theorists developed radically new approaches to representation. In contrast to pre-twentieth century thinking, modern cognitive scientists began working with representational schemes that were inherently nonperceptual" (Barsalou, 1999). To accept the amodal theory would mean that one could convert between modalities and language from a single source. On the other end of the spectrum, a less flexible model for knowledge representation, known as a perceptual symbol system, could tether representations to the modalities with which they were acquired.

At the time of Barsalou's writing, findings from neuroscience were already challenging the amodal symbol theory. Barsalou pointed out several problems with this hypothesis including the fact that there is little direct empirical evidence that amodal symbols exist (Barsalou, 1999). Research in the late 1980s established that categorical knowledge is grounded in sensory-motor regions of the brain (Damasio, A. R., 1989, Farah, M.J., Hammond, K.M., Levine, D.N., Calvino, R., 1988). Modern work on multisensory spatial interactions has further reinforced this understanding (Macaluso, E. Driver, J., 2005). This evidence supports the multimodal hypothesis, which claims that "perceptual symbols are multimodal, originating in all modes of perceived experience, and they are distributed widely throughout the modality-specific areas of the brain" (Barsalou, 1999). Even recalling different forms of sensory information activates different brain regions, as Roland and Friberg found in 1985. They observed that the angular cortex activated during retrieval of numerical memory, while the right mid-temporal cortex was activated during nonverbal auditory memory (Roland, P.E., Frieber, L., 1985).

To better understand interactions between sensory systems, there's been much research into synesthesia, the cross-processing of information from different sensory modalities. Synesthesia mixes the various modalities, allowing for distinguishing properties of one perceptive experience to take representative form in a different experience. Synesthesia conditions are helpful for understanding the relationships between different kinds of knowledge representations in immediate perception and working memory. Serious inquiry into synesthesia has taken place only in recent years, as it was previously believed to be a made-up condition (Sachs, 1812). In 1987, Baron-Cohen, Wyke, and Binnie observed that synesthetes' experiences could be verified behaviourally because they remained noticeably stable over time (Baron-Cohen, Wyke, & Binnie, 1987). This ushered in a new era of research on the condition.

Synesthesia is now understood to be not one, but several conditions, ranging in various dimensions and severity (Grossenbacher, P.G., Lovelace, C.T., 2001). According to Barnett et al, "Not only are there disparate types of synaesthesia, but even within types there are vast individual differences in the way that stimuli induce synaesthesia and in the subjective synaesthetic experience" (Barnett, K. J., et al., 2008). This suggests greater plasticity and less specialization than otherwise thought. Theoretical models based on PET studies, scalp-recorded electrical brain activity, and other empirical findings suggest that synesthesia depends on "synesthetic induction," a type of neural communication which relies on inter-pathway connections and feedback signals, suggesting a high level of interdependence between sensory modalities in the brain (Grossenbacher, P. & Lovelace, C., 2001). Before 2006, there was no standardized psychological scale for measuring synesthesia, which made research into its causes and effects a challenge. In a landmark paper Eagleman et al developed a standardized test battery for studies of the condition, dramatically improving the consistency of such work (Eagleman, D., Kagan, A., Nelson, S., Sagaram, D, & Sarma, A., 2007).

Each of the sensory modalities varies and merits deep examination. These systems are dissimilar in their speeds of transmission, architecture, resource demands, and availability (Meredith, M., Nemitz, J., & Stein, B., 1987). For example, the input of vibrotactile feedback (sensory input from skin contact) is transmitted between .9 and 89.41 miles per second, with a maximum achievable throughput, and undergoes transformations in two parallel procedures (Myers, D., 1995; Novich, S. & Eagleman, D., 2015). The first procedure begins with the somatosensory cortex, which is responsible for transforming the nerve impulses for the sake of object recognition. The second procedure activates emotional processing (such as releasing oxytocin during sex) (Tamè, L., Pavani, F., Papadelis, C., Farnè, A., & Braun, C., 2014). The level of touch detail we perceive, and the efficiency with which we perceive it, are far lesser than what is theoretically available. Take the star-nosed mole for example: thanks to its nose-like appendage, the star-nosed mole is optimally equipped to feel subtle details that serve as hunting cues (Catania, K. and Kaas, J., 1997). This creature's umwelt is, in the case of its sense of touch, richer and more vibrant than that of a human being. As humans, we have only ever lived with a human umwelt and therefore fail to appreciate deficits in our sensory mechanisms and perceptive capabilities. Even writing about our entrapment "on this very thin slice of perception" only presents the limitations abstractly (Eagleman, D., 2015). It is not entirely clear whether or not these limitations should be considered problematic. On one hand, perceiving too much information could overwhelm our limited processing power (Lipowski, Z., 1975). That being said, there's no indication of a limit to what kinds of information our brains can process. We currently sense and process information that was important to survival as evolution sculpted us into anatomically-modern humans.

One of the most valuable sensory modalities for humans is the ability to recognize faces. This capacity allows us to better navigate social dynamics, which are an essential part of human life. Research into this cognitive process began in the 1970s (Ellis, H., 1975). More recently, electrophysiological research has pinned the occipitotemporal cortex as the region primarily responsible for facial recognition, which occurs through fixed, invariant transformations (Truett, A., Puce, A., Spencer, D., McCarthy, G., 1999; Ellis, A., 1992). Open questions remain: Did evolution sculpt the processing of this information as a specialized module of the brain, or does such pattern recognition precede the visual input?

Collecting and processing information about geographical routes is another critical survival skill (Burgess, N., Maguire, E., O'Keefe, J., 2002). In a landmark 1973 review, Hart and Moore explored how humans “come to know and represent in cognition the everyday physical environment,” discussing empirical research on geographic orientation and topographical representations, and the early literature about the development of representations of new or unfamiliar environments (Hart, R., and Moore, G., 1973). In the early 1980s, researchers began probing the process of spatial knowledge acquisition over time. For example, studying the mechanisms of repeated learning trials of selected routes within familiar and unfamiliar neighborhoods (Ggirling, T.; Bf6k, A.; Ergezen, N.; and Lindberg, E., 1981). Today, researchers can observe subjects finding their way in unfamiliar places from the comfort of the lab. Using a virtual-reality town, Hartley et al found that accurate wayfinding activated the right posterior hippocampus, pinpointing a specific modality for this unique sensory ability.

As the decades of work on wayfinding demonstrate, we rely on our mental conception of reality to navigate our world. We find our paths and accept them as fact. This is problematic because our senses can be easily tricked with illusions and misinformation. For example, in court cases, eye witnesses can be subtly manipulated into believing false information as part of their own perceptions (Douglass, A. B., & Steblay, N., 2006).

Limitations to sensation and perception also dictate limitations to language and communication. Without the ability to perceive certain information, we cannot directly engage with it. Meanwhile, this information might govern our world in critical ways. On a very small scale, we fail to directly sense microorganism invaders and genetic information. Existing as tiny, virtually-invisible building blocks of our world, this information has a direct bearing on health and survival. To interact with this information requires we use technology as a middle man of sorts, allowing us to collect data, which we then analyze with other technology. The means to sense, perceive, recognize and react to this information are external to our biology. On a larger scale, we haven't the biological means to sense our cosmos, impending supernova doom, and alien life. The answers we crave are inaccessible to us without technological extensions.

If, however, humans were capable of sensing this information through biological input, would the brain know what to do? Many experiments (such as the synesthesia experiments described above) show that processing structures, conventionally thought of as specialized for one kind of input, can be overtaken by new input. This research suggests a plug-and-play relationship between sensory mechanisms and the brain, which applies both to pre-existing biological sensory input and to arbitrary multidimensional data.

Those without a given sense exhibit enhancement of other senses, whose input can be put to work on the missing sense's related structures. In a 2005 study of the Occipital Cortex, researchers found that blind participants had better hearing than did the control participants who had sight (Amedi, A., Merabet, L., Bermpohl, F., & Pascual-Leone, A., 2005). In this case, sound waves found their way to the visual cortex, where they were processed in such a way that resulted in stronger auditory perceptions. Another study of congenitally blind subjects found that they were better than sighted participants at avoiding obstacles in a virtual navigation task and also within a real life obstacle course using a sensory substitution device known as a "tongue display unit" (Chebat, D., Schneider, F., Kupers, R., Ptito, M., 2011).

In other experiments, researchers encoded non-biological representations of a given biological sensation in a different biological form. Commonly referred to as sensory substitution, providing a sensation representation through another sense can trigger the wiring of new neural circuitry, which identifies patterns and effectively re-creates the perception of the encoded sensation. The earliest sensory substitution research was conducted in 1969 by Paul Bach-y-Rita, who encoded visual stimuli as tactile feedback on the skin of participants' backs. Over time, participants learned to see through touch (Bach-Y-Rita, P., & Kercel, S., 2003). In a 2016 experiment, deaf participants using this kind of encoding technology were able to regain their ability to take in and process verbal language (Brogaard, B., Marlow, K., Overgaard, M., Schwartz, B., Zopluoglu, C., Tomson, S., Eagleman, D., 2017). From existing sensory substitution research, it stands to reason that specialized sensation processing modules can work on the information from other sensory mechanisms, or raw data for that matter.

Recent iterations of sensory substitution experiments reveal that the brain can make sense of much more than visuals or other conventional input. Neuroscience researcher David Eagleman baffled TedX audiences in 2015 when he revealed that he was wearing a sensory substitution vest, which was encoding viewer feedback in real time (Eagleman, D., 2015). While his brain had not yet rewired to make sense of the data mid-talk, it posed a question that could unlock the untapped value of big data: can the human brain be used as a tool for the analysis of specialized data? The increasing ubiquity of computing and internet powers have given rise to a vast increase in data collection ability. This data carries hidden insights into every conceivable aspect of our existence: how do we cure cancer, what lies on the inside of a black hole, how can I manipulate someone into spending their retirement on a kitschy collector's bobblehead? The applications of this data could enhance our lives greatly, or it could affect us for the worse. Hopefully, data insights will be used to benefit individuals, as opposed to being used for the economic gain of big data corporations. Regardless of the ethics of big data, there is much progress to be made by way of analysis. In his talk, Eagleman went on to offer several possible applications of feeding data into the brain. He described how the brain could detect patterns of the global economy within stock market data, or how it could understand space station status data for simpler monitoring (astronauts spend most of their time ensuring the stability of their station). Previously, one would need to sense the data, represented in a given modality, and then re-transform the perception for deeper analysis. The value in feeding data directly into the brain is that we no longer have to process the abstraction; instead of indirectly accessing the data, we experience the data. This allows our brain to go to work unlike ever before.

Other applications of sensory substitution with specialized data could promote greater health in individuals. There are numerous smartphone applications which seek to draw insights from user sleep cycles. Unfortunately, the algorithms with which they operate are lacking in scientific validity (Ong, A., Gillespie, M., 2016). If one was fed sleep-cycle data, they would likely identify correlations between their sleep behavior and other factors. Over time, this awareness could help them overcome health issues relating to sleep. Similarly, eating habits plague the majority of Americans. Beyond simple obesity, harmful diet deteriorates the microbiome, which can result in many kinds of currently-incurable autoimmune disease. While research suggests that technological solutions can successfully identify data relating to necessary habit change, it also suggests that the reception of feedback is critically underdeveloped (Levine, D., Savarimuthu, S., Squires, A., et al., 2014). Feeding health data directly into the brain would allow individuals to better understand the consequences of their behavior. Ultimately, it could be a tool for combatting behavioral and substance addictions. This applies even to the most minor of connections, such as indulging an emotional response which spikes the release of cortisol in the blood stream. While much of our sensation processing is devoted to the outside world, it would benefit us greatly to shift the focus to ourselves internally.

With the ability to process literally any information, we must pick and choose what information is most important to us. So let’s take a look at what mother nature has already provided. Honeybees can see ultraviolet light, which allows them to effectively scout out the flower pedals with the greatest nectar contents (Kevan, P., Chittka, L., Dyer, A., 2001). Snakes can see infrared, which allows them to identify warm-blooded prey and avoid environments where they’re prone to cold-blooded stagnation (Ebert, J., 2007). The Mantis Shrimp sees 16 base colors, whereas humans only see three. To experience this world of greater color variety could be breathtaking (Thoen, H., How, M., Chiou, T., & Marshall, J., 2014). Black ghost knifefish can detect electrical fields, which allows them to forage for insect larvae (Nelson, M., & Maciver, M., 1999). Bats can detect air compression waves, which would be useful to humans as it allows for a form of object recognition in complete darkness (and would therefore be a good alternative to sight) (Pye, J., 1968). Pigeons are aware of the earth’s magnetic poles with a sensory mechanism known as “magnetites” (Kirschvink, J., & Gould, J., 1981). This gives pigeons a built-in compass for wayfinding during migration, something that the human wayfinders described earlier would certainly benefit from.

Beyond what exists in nature, we can decide what sensory mechanisms to implement based on existing technologies. Digital camera technology can capture visual information in much greater detail than does the human eye. Shotgun microphones can pick up on conversations from hundreds of feet away. Beyond updating ourselves with technological versions of our sensory mechanisms, we could open the door to entirely new kinds of sensation. The light waves that we are capable of sensing account for less than a ten-trillionth of possible electromagnetic radiation. The ability to sense radio spectrum information would be of particular benefit to us, as it would allow the human brain to directly interface with technological systems such as cellular networks (the internet) and, ultimately, with one another (telepathy). Currently limited to five, sometimes-impotent senses, we are beginning to develop a toolkit for redesigning our umwelt.

In 2017, this toolkit is actually rather elaborate. Researchers are making formative decisions about how to best establish this new paradigm of transhuman sensation and perception. Those with a defective sensory mechanism can use technological solutions such as cochlear and retinal implants, which provide artificial hearing and vision respectively (House, W.F., 1976; Zrenner, E., 2002). LASIK procedures can restore and even enhance the patient’s vision (Solomon, K.D., et al., 2009). Technological solutions to loss of or deficits in a sensory mechanism are effective, yet they are also invasive, costly, and unavailable to a large portion of the population. To experience similar (if not the same) benefits without invasive procedures, consumers can turn to sensory substitution devices. “Brainport” for instance, is a consumer sensory substitution device (SSD), which functions by translating a video feed into electric impulses on a grid that sits on the user's tongue (Arnoldussen, A. and Fletcher, D., 2012).

In the future, the addition of sensory mechanisms is likely to occur through genetic engineering. CRISPR (Clustered Regularly Interspaced Short Palindromic Repeat) sequences were initially discovered in the E. coli genome in 1987 (Ishino Y., Shinagawa H., Makino K., Amemura M., Nakata A., 1987), but their potential for use as a genome editing tool was not discovered until 2012 when Jennifer Doudna's research team demonstrated that CRISPR could be used to cut DNA in a programmed way in vitro (Jinek M., et al, 2012). Traditional gene editing approaches such as zapping cells with radiation and hoping for random mutation or zinc-finger nucleases are either error-prone or limited in the genomic regions they can target (Gupta, R., Musunuru, K., 2014). CRISPR, on the other hand, is incredibly accurate: it targets a specific snippet of DNA and swaps it with another (Jinek M., et al, 2012). Not only is accurate, but it is also simple, inexpensive, agile, and works on every kind of cell. After four years, we are now beginning to see the first CRISPR treatments being used on human beings (Ma, H. et al., 2017). While the first applications of this biotechnology are intended fight life-threatening genetic disease, it may soon be applied to weed out undesirable genetic information from the human gene pool.

Without touching on the ethics of eliminating deafness and blindness from the gene pool, we can assume that such modifications will be available soon. Next, we'll begin to do more than simply eliminating bad genetic information; we'll create new genetic information. Drawing on animal traits such as those mentioned earlier in this paper, human beings could begin to manipulate sensory mechanisms on a genetic level. We might give ourselves the very best sense from the mammalian kingdom. We could make our experience of everyday life more vibrant and pleasurable. Ultimately, we may well create sensory mechanisms that never existed in past life forms (360º vision, for example). With this advancement, life as we know it will undergo radical transformation. This place in our evolutionary timeline (transhumanism as a common phenomena) could be met with other advancement, such as artificial extension of human intelligence, which takes application priority over genetic engineering. Still, assuming that our evolution does go in the direction of self-driven evolution via gene editing and technological extension, what could go wrong?

One criticism of such a future is that we might throw our umwelt out of balance; the creation of new neural pathways for new senses could result in hallucinations or misinformation, as when newly sighted people initially fail to interpret visual input (Held, R. et al., 2011). The re-allocation of limited cognitive resources might also detract from elements of perception to which we've grown attached (Mitchell, A. & Lim, W., 2016). In understanding this give and take between resources, there is a demand for a "correct" model of neuroplasticity. This model must account for specialization, as well as flexibility and everything in between. While it would be nice to believe in a "Potato Head" model, in which sensory mechanisms can change without placing demand for change on the brain, it is unlikely that the neural correlates are this simple. There are likely to be many rules to the reusability of specialized modules and to the behavior of neuronal rewiring for new kinds of pattern recognition. The field of neuroscience lacks an accurate or explicitly-correct model to describe these rules. We currently understand the brain as a hackable information processor. It is shielded from the outside world, and will attempt to extract patterns, and assign semantic value to the information it is fed. This recognition is biased to align with pre-existing internal knowledge representations (Wiech, K., 2016). While numerous often-conflicting models attempt to further detail neuroplasticity, there are no certainties. This makes it impossible in 2017, using empirical evidence, to safeguard against harmful redistribution of cognitive resources. Nevertheless, an optimally-functional balance between sensory mechanisms and other input must exist, and will be further pursued in the years to come.

Other criticisms are rooted more so in philosophy than in neuroscientific models. Acclaimed modern philosopher Jurgen Habermas explores various concerns in his 2003 book "The Future of Human Nature." In this work, he claims that while humans are moral agents capable of controlling their life plan, "genetic alteration imperils my autonomy and standing as a moral agent" (Habermas, J., 2003). On the other hand, philosopher Julian Savulescu believes in "moral transhumanism," arguing that humanity will destroy itself unless we genetically modify ourselves to be less violent. He writes, "It is unimportant that humans remain biologically human, since they do not have moral value in virtue of belonging to H. sapiens" (Persson, I. & Savulescu, J., 2010). While much of Savulescu's focus is on genetic roots of behavior, his writing touches on idea of redesigning cognitive processes, many of which are linked to perception. The pitfall of a redesign could be unintentional alterations to the priorities of our species. While we'd do well to eliminate many of the triggers for aggression and interpersonal conflict, it would be disadvantageous to make any major alterations without first knowing possible chain reactions. If, for instance, we enhanced touch sensation mechanisms, humans could become (even more) overly-preoccupied with sexual pursuits. Human behavior could move in a direction counter to our current view of a positive future.

In light of the historical research and possible futures outlined in this paper, we can suggest an answer to the question: do we experience a true version of our existence? As we have seen, what is "true" varies by species, and across the range of human experience. It can be manipulated by illusions or supplemented with technology. Now, with the ability to consider self-driven evolution of sensation and perception, human beings are at a turning point in the history of life. In the near future, if the information our brain takes in can bypass conventional sensory mechanisms, we might be able to escape the limitations and complexities explored in this paper in favor of a more deeply integrated existence. We may yet come to experience a truer existence than ever before available.

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