Conscious Sensation, Conscious Perception and Sensorimotor Theories of Consciousness

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Abstract. This article explores the hypothesis that the differences between our conscious sensations (color, sound, smell, etc.) could be linked to the different ways in which our senses process and structure information. It is also proposed that the organization of our conscious sensations into a conscious perception of a three-dimensional world could be linked to our mastery of sensorimotor contingencies. These hypotheses are supported by a number of observations, including the appearance of conscious sensations without motor action and the apparent failure of sensory substitution systems to generate visual sensations in congenitally blind subjects. The article discusses how the correlates of conscious sensation and perception could develop in the brain and some suggestions are put forward about how this account could be experimentally tested.

Keywords: consciousness, sensation, sensory substitution, perception, sensorimotor contingencies, correlates of consciousness.

1 Introduction

This article explores the hypothesis that the differences between our conscious sensations (color, sound, smell, etc.) could be linked to the different ways in which our senses process and structure information.[1] It also proposed that our sensorimotor interactions with our environment enable us to organize these sensations into a consciously perceived three-dimensional world. I will start with some definitions that will enable me to state these hypotheses more precisely:

- *Sensory contingencies*. Different senses have highly characteristic ways of processing information from the world. For example, the photoreceptors in the retina have a variety of response characteristics and spatial distributions, and they are wired up in complex ways to bipolar, horizontal, and ganglion cells, which work together to produce complex patterns of spikes in response to light. The other senses (sound, taste, smell, proprioception, etc.) also have unique spatiotemporal

[1] In this article I am using 'information' in a loose non-technical sense. In other work [1] I have suggested how Floridi's [2] approach could help us to develop better ways of identifying information in the brain.

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response characteristics that process information in complex ways. The different ways in which the senses process incoming information will be referred to as *sensory contingencies*.

- *Sensorimotor contingencies*. Perception is an active process in which we move our eyes and body to acquire sensory information. The specific ways in which these sensorimotor patterns are structured are called *sensorimotor contingencies*. For example, when I am looking at a line the sensory information remains unchanged as I move my eyes along the line, and it alters when I move my eyes across the line.[2] When I move my hand from left to right, the visual image of my hand changes in a predictable way.
- *Conscious sensations*. I will use the term *conscious sensations* to describe the qualitative aspects of our experience, such as red, pain, birdsong, the taste of chocolate, and so on. Although 'qualia' is more commonly used to describe these phenomena, it is a controversial philosophical term, and 'conscious sensations' has the advantage that it is explicitly connected with the senses and can be more naturally contrasted with unconscious sensations.
- *Conscious perception*. This is our normal experience of perceiving our environment. While conscious sensations can appear without being referred to a cause or object (see Section 2.1), they are typically integrated into a consciously perceived three-dimensional world – for example, I see a red bird on the ground, smell it and hear the rustle of its feathers. A crude way of picturing the distinction between conscious sensation and conscious perception is that conscious perception provides an integrated three-dimensional framework that is 'filled in' with conscious sensations.

This article will explore the following hypotheses:

H1. Conscious sensations are correlated with sensory contingencies. The differences between the sensory channels' information-processing can be used to explain and make predictions about the qualitative differences between conscious sensations - for example, the difference between color and sound.[3]

H2. Conscious perception is correlated with our mastery of sensorimotor contingencies. Our interactions with the world teach us the relationships between motor outputs and sensory inputs. This enables us to structure our conscious sensations in a consciously perceived three-dimensional space centered on the body.[4]

The context and level of intensity of incoming sensory information determine whether it is experienced as conscious sensation (a sudden noise, pain, buzzing on the skin) or integrated with proprioceptive and motor information to produce conscious perception.

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[2] This example is from O'Regan and Noë [3].

[3] A version of this hypothesis is defended by Keeley [4], who gives a useful summary of previous philosophical work on the differences between the senses.

[4] This account of the perception of the external world is similar to Aleksander's notion of depiction [5].

While some authors have suggested that there is an identity between a mastery of sensorimotor contingencies and consciousness [3, 6, 7], I am only focusing here on the weaker and less contentious claim that there might be a correlation between sensory or sensorimotor contingencies and the contents of consciousness. Since I am only examining the correlates of different types of content, I will set aside questions about the correlates of the level of consciousness. Given that a brain is conscious, I want to know why a particular pattern of activity is correlated with a conscious sensation of red instead of green, or with a sound instead of a smell?[5]

Some sensorimotor theories tend towards the view that patterns of activity in the brain *and world* are correlated with conscious states [6]. This fails to explain situations in which the contents of consciousness are disconnected from the world, such as dreams, out of body experiences, memories, hallucinations, or when the brain is stimulated with electrodes or TMS. In this article I will focus on the more plausible hypothesis that neural activity patterns in the brain are correlated with conscious contents. The brain learns these patterns by interacting with the world; when they are reactivated in a trained brain they can potentially be correlated with conscious contents independently of the current environment (see Section 3).[6]

The first part of this article puts forward a number of observations that support a dissociation between conscious sensation and sensorimotor contingencies. I will then suggest how the correlates of conscious sensation and perception could emerge in a developing brain. Some ways of experimentally testing H1 and H2 are then put forward, followed by a discussion of how they relate to the sensorimotor theories of O'Regan and Noë. The article concludes with some implications of these hypotheses.

2 Conscious Sensations and Sensory Contingencies

This section highlights a number of situations in which conscious sensations occur without motor action, which suggests that they are unlikely to be correlated with or identical to sensorimotor contingencies. The research on sensory substitution systems suggests that conscious sensations are linked to sensory contingencies and sensorimotor contingencies are associated with our conscious perception of a three-dimensional world.

[5] This is broadly in agreement with Chalmers' definition of the neural correlates of the content of consciousness: "An NCC (for content) is a minimal neural representational system N such that representation of a content in N is sufficient, under conditions C, for representation of that content in consciousness." ([8], p. 31).

[6] See [3, 6] for attempts to resist this position, which in my view are unconvincing. While O'Regan [7] acknowledges that brain stimulation could induce conscious sensations (p.108), he claims that conscious sensations are qualities of ongoing interactions between the brain and world, not some kind of essence that is generated by the brain. Some of the commentary on [3] discusses this issue, which is covered in more detail in Section 5.1.

2.1 Conscious Sensations without Action

A number of observations support a dissociation between conscious sensations and motor action. First, we often experience conscious sensations without having made a motor action. For example, I am sitting passively in the dark and a bright light is suddenly switched on. I initially experience a raw sensation of blinding light, and then my eyes adapt, I start to saccade and I perceive a structured world. The phenomenology is similar with a sudden noise: at first I am startled by the noise, which swamps my senses and I am consumed by the sensation of it; some moments later I locate the source and nature of the sound.

Second, experiments have shown that conscious sensations can be produced by very brief stimuli – for example, a 1ms flash of light can cause a conscious visual sensation; a conscious auditory sensation can be elicited by a 1ms auditory click [9]. The duration of these stimuli is much less than the timescale of motor actions that could actively explore them (the eyes saccade every ~200ms; ear and head movements take much longer).

Third, many conscious body sensations, such as heartburn and pain, do not have an obvious motor component – they just happen to us and we do not have to move or do anything to make them happen or go away. All of these observations suggest that motor action is not necessary for conscious sensations.[7]

2.2 Direct Brain Stimulation Produces Conscious Sensations

Conscious sensations can be evoked by directly stimulating the brain of a passive subject. For example, a blow to the head, a TMS pulse or electrode stimulation produces phosphenes, memories, body sensations and sounds [10, 11].

2.3 Sensory Substitution Systems

The phenomenology of people's use of sensory substitution systems is easily explained by a distinction between conscious sensation and perception. For example, in a tactile visual substitution system (TVSS) a two-dimensional array of vibrators is placed on the body[8] and connected to visual information from a camera that is typically mounted on the head [12]. If the subject does not move, they typically experience a buzzing on the surface of their body. While little or no explanation of this buzzing sensation is offered by a sensorimotor theory of consciousness, it becomes easier to understand if there is a correlation between somatosensory contingencies and conscious buzzing sensations (H1).

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[7] O'Regan [7] acknowledges that vision can occur without action, and claims that being poised for action is enough, even if the action is not executed (p. 67).

[8] In some TVSSs a two dimensional array of electrodes is placed on the tongue: a small voltage produces a tingling sensation.

When subjects are allowed to move the camera, the buzzing sensation is transformed into perception of a spatially organized world.[9] However, although congenitally blind subjects can use a TVSS to perceive a three-dimensional environment, this is not enough to give them a conscious sensation of light. Visually handicapped people expressed disappointment with these devices for this reason [13].[10]

The absence of conscious visual sensations in congenitally blind subjects is supported by a study in which normally sighted and congenitally blind subjects were trained on a tongue-mounted TVSS. Before training the blind subjects did not report any tactile sensations on their tongues when TMS was applied to their visual cortex. After training the TMS caused some of the blind subjects to experience somatopically organized tactile sensations on their tongues. The application of TMS to the same brain areas of the normally sighted subjects caused them to experience visual phosphenes both before and after the training [15]. This suggests that the TVSS training increased the blind subjects' ability to perceive the world through tactile sensations on their tongues, but it did not give them the conscious sensation of light.[11]

While H1 predicts that congenitally blind subjects using a TVSS will not experience conscious visual sensations, a limited amount of visual experience would be expected in non-congenitally blind or normal subjects. Once these subjects have learnt to use the TVSS, they can use their memory and imagination to generate visual images of the world that they are perceiving through the buzzing sensations. There are also a considerable number of cross-sensory connections in the brain, which could lead to visual areas being activated in response to other sensory stimulation - a phenomena that appears most strongly in synaesthesia.

The limitations of sensory substitution systems also support a dissociation between conscious sensations and sensorimotor contingencies. While some success has been achieved with devices that substitute vision using audio or somatosensory stimulation, no-one has created a taste or pain sensory substitution device, and it is very difficult to imagine how this could work. We might try to build a vision-taste substitution system by giving a person a tasteless object to chew while they look at a display showing the sensory patterns that are produced by the taste receptors [18]. However, it seems inconceivable that such a system could evoke the sensation of bitterness or

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[9] Subjects have to spend some time practicing with the device before this occurs.

[10] The first person report of a congenitally blind person's experience with a TVSS [14] is sometimes cited as a counter-example to this claim. However, Guarniero's description of 'seeing' with the device is much more akin to spatial perception, than encountering what for him would be a novel conscious sensation: "As I have noted at the beginning of this paper, I have used the word 'see' for lack of a better. The difficulty is not merely one of vocabulary; rather it is a conceptual one. Very soon after I had learned how to scan, the sensations no longer felt as if they were located on my back, and I became less and less aware that vibrating pins were making contact with my skin. By this time objects had come to have a top and bottom; a right side and a left; but no depth – they existed in an ordered two-dimensional space, the precise location of which has not yet been determined." (p. 104)

[11] Similar interpretations of TVSS experiments are given by Keeley [4], Block [16] and Prinz [17].

sweetness in a subject, and similar problems exist with the substitution of pain or smell.[12,13]

2.4 Ockham's Razor

Some theories of consciousness claim that sensorimotor patterns can be used to explain the differences between our senses (for example, [3]). However, if sensory contingencies contain enough information to differentiate the senses, then it might not be necessary to include motor actions in our explanations as well. If we are looking for a *minimal* set of spatiotemporal structures in the brain that are correlated with conscious sensations, then we should start with sensory contingencies, and carry out experiments to see if these provide enough information to make accurate predictions about conscious contents (see Section 4).

2.5 Conscious Sensations without Sensorimotor Contingencies

In some situations people experience conscious sensations that they cannot systematically integrate with their actions [19]. For example, people who have had their sight restored after a cataract operation often have mixed-up sensations of color, movement and light and do not know how to use their eye movements to perceive the world [20]. A similar situation occurs when people wear inverting glasses that disrupt the normal relationship between changes in the visual world and eye and body movements. When subjects put on these glasses they are initially extremely disoriented and find it very difficult to perceive or interact with the world. Gradually they mastery the sensorimotor contingencies of the inverting glasses and learn to perceive and act in the world again [21].

While Noë [19] describes these situations as 'experiential blindness', it is more accurate to describe them as cases of perceptual blindness, since the subjects can experience a variety of color, light and movement sensations. They are perceptually blind because they do not know the sensorimotor rules that would enable them to coordinate their experiences into a consciously perceived world. People become experientially blind (lose conscious visual sensations) if their sensory apparatus (eyes, optic nerves, visual cortex, etc.) is damaged.

3 The Correlates of Conscious Sensation and Perception

The observations outlined so far suggest that there is a connection between conscious sensations and sensory contingencies in the brain. However, conscious sensations

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[12] One way of explaining the limited success of sensory substitution systems is that they provide information that can be accessed through a number of different sensory channels, but they cannot substitute information that is only present in a single sensory channel.

[13] Some of these points were made by Fiona MacPherson in her talk 'Sensory Substitution and Augmentation: Introduction to the Issues' at the conference on Sensory Substitution and Augmentation, British Academy, London, 26th March 2013.

cannot be directly correlated with the low-level processing of the individual senses because they can occur without the activation of the sensory hardware – for example, conscious visual sensations can be triggered by TMS independently of the retina. A more plausible hypothesis is that the cortical areas connected to each sensory channel learn to respond to the sensory contingencies of that channel, which enables them to reproduce the sensory contingencies in the absence of stimulation from the senses. Research on the neural correlates of consciousness has indicated that low level sensory areas, such as V1, are only weakly correlated with consciousness [22]. This suggests that the brain areas which are correlated with conscious sensations are likely to be higher up the sensory processing hierarchies.

The developing cortex is only roughly wired up using chemical gradients and other mechanisms, and so the differences between our conscious sensations are unlikely to be linked to genetically wired connection patterns. It is more likely that the developing cortex learns to respond to incoming sensory patterns using synaptic pruning and other processes, which leads to substantially different structures and response characteristics in the different sensory areas [23]. In the womb the data that it is available for this learning process includes random noise in the sensors (retina, cochlea, etc.) and environmental stimulation (sound, light, taste and smell). Once a cortical area has learnt to respond to a set of sensory contingencies, artificial stimulation of the area will produce a noisy version of the corresponding sensation – for example, TMS stimulation of trained visual cortex leads to phosphenes.

The structuring of the cortex in response to sensory stimulation patterns has been experimentally demonstrated in ferrets and hamsters. For example, in work carried out by Sur et al. [23] the visual pathways in neonatal ferrets were redirected to the auditory cortex. Many of the neurons in the rewired auditory cortex developed visual response characteristics similar to those in V1, although there were some differences between orientation selective cells in V1 and the rewired cortex.[14] Similar results have been obtained in rewired hamsters [24], whose visually guided behavior was similar to controls [25].[15]

The development of the mechanisms linked to conscious perception probably occurs during late embryological development and after birth, when the child learns how its motor actions generate predictable patterns of sensory information. This probably strengthens the connections between the learnt sensory contingency patterns, proprioceptive areas and motor output areas.

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[14] Some of the differences between rewired visual cortex and normal visual cortex could be due to the fact that the rewiring was carried out postnatally.

[15] It might be objected that people who have had their sight restored by a cataract or cornea operation have conscious visual sensations, although their cortex has apparently had no chance to learn to respond to visual information during early childhood. However, this type of operation is only carried out on patients with functional retinas [20]. This type of subject perceives a limited amount of light through the surface of the eye, which is enough to stimulate the cortex with visual sensory contingencies.

4 Testing H1 and H2

The first step in the testing of hypotheses H1 and H2 is the recording of cortical activity in which the sensory and sensorimotor contingencies that might be correlated with conscious contents can be found. A variety of techniques can be used to identify mathematical regularities in this data, which can be used to generate testable predictions about conscious sensations and perception.

4.1 Data

The first step in the recording of data is the identification of the parts of the brain that contain the sensory contingencies which could be correlated with conscious content. These can be identified by experiments on the correlates of consciousness, using binocular rivalry, the subliminal presentation of stimuli or other techniques [22]. Once appropriate areas of the brain have been identified we need to record the sensory and sensorimotor contingency patterns that the cortex has learnt as a result of its stimulation from the senses.

This type of data is difficult to record in humans because of the low spatial and/or temporal resolution of fMRI and EEG, and electrodes can only be implanted in a limited number of sites when patients are being operated on for other reasons. In animals optogenetic techniques are reaching the point at which they can record from up to 100,000 neurons at 1 Hz from zebrafish larvae [26], and it is becoming possible to record from a few tens of thousands of neurons close to the surface of the cortex of a mammalian brain. The problem with using data recorded from animals is that their sensory contingencies are likely to be very different from our own, and so predictions about conscious sensations based on this data are likely to be specific to the animals that it is taken from.

A more systematic way of understanding how the cortex learns sensory contingencies would be to prepare samples of embryological cortical tissue and expose them to patterns of activity from different senses. The stimulation patterns could be generated using spike conversion libraries, which have been developed for visual, proprioceptive and auditory data [27, 28]. If the picture sketched out in Section 3 is correct, these pieces of cortex should self-organize in response to the incoming data and exhibit different spontaneous activity patterns once they had been trained. To minimize the difficulties of working with in vitro tissue, this approach could be prototyped on simulated neural tissue – the models developed by Izhikevich and Edelman [29] or Markram [30] would be good starting points for this work.

4.2 Mathematical Regularities in the Data

Once the sensory and sensorimotor contingency patterns have been recorded we need to find a way of describing these patterns that is generalizable across individuals and can make accurate predictions about conscious sensations and perceptions. The research on brain reading using fMRI has used inferred models and statistics to make fairly accurate predictions about conscious contents, to the extent of decoding people's dreams [31] or reconstructing the videos they are watching [32]. However, these techniques are based on data with low spatial and temporal resolution, and they typically have to be fine tuned for each individual. This suggests that they have not completely captured the correlates of conscious contents in the brain.

An alternative way of tackling this problem would be to take inspiration from physics and look for mathematical regularities in the sensory and sensorimotor patterns that are not specific to any individual person. These could be expressed using sets of differential equations, category theory or some other mathematical formalism. The mathematical equations in physics are typically written down by an expert scientist, and this approach has been taken in consciousness science by Tononi [33], who has developed algorithms for generating a mathematical structure that is predicted to correspond to the contents of consciousness.

The central problem with the use of an expert scientist to compose the equations is that the regularities that develop in the cortex in response to sensory and sensorimotor contingencies might be too complicated to be captured in equations that are written down by a human. To avoid this problem, machine learning techniques could be used to infer the equations from recordings of cortical data. A computational approach to the discovery of scientific knowledge has shown promise in a number of areas [34-36], and it could be a good way of identifying potentially complex regularities in brain activity patterns that are correlated with conscious sensation and perception.

A more radical approach would be to develop a mathematical model of how data is transformed by the senses and learnt by the cortex [37]. While it would be more elegant to infer the sensory contingencies from the structure of the sensory apparatus, the ways in which the cortex learns to respond to this information might be too complex for an analytical mathematical treatment.

4.3 Predictions

Once the sensory and sensorimotor contingency patterns have been identified and mathematically described they could be used to make predictions about conscious sensations and perceptions in humans.[16] One approach would be to use the inferred mathematical regularities to make predictions about how sensory and sensorimotor contingencies would appear in fMRI or EEG data. Ideally the model should be able to specify how the sensory contingencies corresponding to different colors, sounds, etc would appear in an fMRI or EEG recording, which would enable testable predictions to be made about subjects' first person reports.

[16] Predictions about conscious content in animals are difficult to test. While they can generate a behavioral output in response to a stimulus that is assumed to be conscious, they have no way of describing their conscious contents.

5 H1 and H2 in Relation to Other Sensorimotor Theories

While the hypotheses of this paper have been influenced by O'Regan and Noë's work on sensorimotor theory [3, 6, 7, 19], there are important differences between H1 and H2 and their account of conscious experience. O'Regan and Noë would be likely to broadly agree on the following points:

1. The brain does not contain a rich set of internal representations of the world.
2. Conscious sensations are linked to sensorimotor contingencies.
3. Conscious perceptions are linked to sensorimotor contingencies.
4. While the brain plays a role in conscious sensation and perception, the world is likely to be necessary for some types of conscious experience.
5. Sensorimotor theory can explain the link between physical world and consciousness.

In this paper I have argued that conscious perception is linked to our mastery of sensorimotor contingencies (H2) and I have focused on a correlates-based approach to consciousness that does not seek to explain the relationship between the physical world and consciousness. I also think that the physiology of the eye and research on change blindness and inattentional blindness (for example, [38, 39]) demonstrate that we do not have a rich set of internal representations that accurately track the world. This leaves two main points of disagreement: the extent to which brain activity is correlated with consciousness and the link between sensorimotor contingencies and conscious sensation. I will consider these in turn.

5.1 Consciousness and the Brain

A significant difference between the position outlined in this paper and sensorimotor theorists, such as O'Regan and Noë, is the idea that conscious sensation and perception are correlated with brain activity alone, rather than with the brain and world (see Section 1). For example, in their joint paper O'Regan and Noë [3] claim:

> There can therefore be no one-to-one correspondence between visual experience and neural activations. Seeing is not constituted by activation of neural representations. Exactly the same neural state can underlie different experiences, just as the same body position can be part of different dances. (p. 966)

A less radical position can be found in Noë's [19] later work: "A reasonable bet, at this point, is that *some* experience, or some features of some experiences, are, as it were, exclusively neural in their causal basis, but that full-blown, mature human experience is not." (p. 218). To discuss the role of the brain in relation to O'Regan and Noë's theories, I will distinguish between two types of conscious experience:

1. *Online conscious perception*. Detailed information from the environment can be accessed on demand. Colors are vivid; sounds are loud and clear; objects are stable.

2. *Offline conscious experiences.* These include experiences induced by brain stimulation, dreams, imagination, phantom limbs, out-of-body experiences and hallucinations Offline conscious experiences are often unstable, low resolution and low intensity, and their content is independent of the state of the environment. Conscious sensations are present in some or all of the sensory modalities and the states are weakly perceptual – for example, we see objects but cannot interact with them in a systematic way.

Although there is some overlap between these two types of experience (for example, people can mistake phantom limbs for actual limbs [40]), they are reasonably distinct categories for most people. Since the first type of experience is typically produced as the brain interacts with its environment, it is difficult to prove that it is just correlated with brain activity. In the second type of experience, conscious sensations and a limited form of conscious perception occur without any interaction between the brain and its environment, which suggests that the second type of experience is correlated with brain activity alone.

While it has not been proved that online conscious perceptual experiences are solely correlated with brain activity, it seems reasonable to make this into a working assumption, which can be tested using the experimental approach outlined in Section 4. Noë's bet that this type of conscious experience is not exclusively correlated with neural activity is a different working hypothesis, which can also be experimentally tested.

5.2 Conscious Sensations and Sensorimotor Contingencies

A substantial amount of evidence was presented in Section 2 which strongly suggests that conscious sensations can occur without motor action. This supports a dissociation between conscious sensations and sensori*motor* contingencies. This would be falsified if conscious sensations could be produced without the activation of sensory contingency patterns in the cortex - for example, if the conscious sensation of red could be induced by a TVSS.

Section 2.3 set out evidence in favor of the claim that no device capable of inducing conscious sensations has been created. While O'Regan [7] cites Guarniero's experiences with the device as a possible counterexample, I argued in Footnote 10 that Guarniero's description of 'seeing' with the device is much more akin to spatial perception, than encountering what for him would be a novel conscious sensation. O'Regan [7] also suggests that the limited capabilities of the current sensory substitution systems are likely to be preventing them from inducing conscious sensations:

> …current techniques of visual-to-tactile and visual-to-auditory substitution are a long way from the goal of achieving a real sense of vision. Using tactile or auditory stimulation, it is possible only to provide a few aspects of normal visual impressions, like the quality of being "out there" in the world, and of conveying information about spatial layout and object form. But the "image-like" quality of vision still seems far away. Indeed, because the eye is such a

> high-resolution sensor, it will probably never be possible to attain true substitution of the image-like quality of vision. (pp. 142-3)

O'Regan goes on to discuss other substitution systems, such as a glove designed to provide touch sensations for leprosy patients [41] and vestibular substitution systems. In the glove experiments, subjects experienced touch sensations on the forehead as if they were on the glove However, this is not an example of sensory *substitution* because it only altered the location of a conscious sensation - it did not provide the information from one sense through a different sensory channel. The apparent success of vestibular substitution systems also does not count against H1 because vestibular information is not obviously correlated with conscious sensations.

It might be claimed that a device capable of sensory substitution could be created, and that the possibility of this device invalidates H1. However, people have very different intuitions in this area and imagination and thought experiments are rarely an accurate guide to what is possible in the real world. While I agree that H1 would be invalidated by an actual sensory substitution device that induces conscious sensations, the question cannot be decided by people's competing intuitions about whether this could or could not be constructed.

6 Discussion and Conclusions

This article has argued that the qualitative aspects of conscious experience (conscious sensations) are correlated with sensory contingencies (H1), and that the organization of conscious sensations into a three-dimensional consciously perceived world is linked to our mastery of sensorimotor contingencies (H2). I have suggested that the sensory and sensorimotor patterns that are correlated with consciousness are located in the cortex, which learns to respond to the output of the different sensory channels. The hypotheses of this paper can be tested by using machine learning techniques to infer mathematical descriptions of sensory and sensorimotor contingency patterns, which can be used to generate predictions about conscious sensations and perceptions.

This article's approach to conscious content could extend and complement previous theories about neural representation that have been put forward. For example, it has been suggested that the place of a neuron in a hierarchy or population determines its representational content, and there are a number of interpretations of the neural code (for example, firing rate or spike timing relationships). The problem with these theories of neural representation is that they are generally based on correlations between neural activity and states of the world, which limits their ability to systematically account for differences in conscious contents – for example, why pattern P in population X is correlated with a red sensation and pattern Q in population Y is correlated with the sound of a police siren. In this article I have put forward a more theory-driven approach, which could improve our ability to identify correlations between neural activity and conscious sensations and perceptions.

The distinction between sensory and sensorimotor contingencies can help us to understand some of the limitations of sensory substitution devices. While they can successfully encode sensorimotor contingencies, they cannot alter or replace the contingent ways in which the sensory channels process information, and so people using them do not have the conscious sensations that correspond to the substituted sense (vibrations on the tongue do not induce conscious visual sensations). To effectively substitute conscious sensations, it would be necessary to model the sensory contingencies of a particular sense and feed the information directly into the cortex.

While sensory substitution systems have succeeded in transforming and augmenting our current sensations and perceptions, it is debatable whether they have been able to generate novel sensations.[17] According to the hypotheses put forward in this article, a novel conscious sensation could be induced in a subject by a sensory channel with unique sensory contingencies. This would have to be directly connected to the cortex, which would have to learn to respond to it over an extended period. Although optogenetics or implanted electrodes would be ideal for this task, there are few situations in which these can be used in human subjects. A more practical method would be to use focused ultrasound [43] or high-definition transcranial direct current stimulation to deliver an appropriate signal to the brain.[18] Alternatively, it might be possible to use an inverse model to cancel out the sensory contingencies of a particular channel. For example, perhaps one could develop an inverse model of the retina and early visual cortex and apply this to visual data to cancel out the effects of visual processing. This might enable data free of visual sensory contingencies to be passed directly to the brain. Further research is needed to determine the feasibility of this approach.

This article has focused on the possibility that conscious sensations could be correlated with sensory contingencies. I have not attempted to address the 'hard' problem of consciousness or tried to *explain* the relationship between patterns of brain activity and conscious sensations. Elsewhere I have argued that our inability to imagine the physical world will make it impossible to develop an intuitively satisfying explanation of the relationship between consciousness and brain activity.[19] However, empirical work on the correlates of consciousness could lead to the development of mathematically formulated theories that can map with high accuracy between brain activity and conscious states. This might make us more willing to abandon our desire for intuitively satisfying explanations in consciousness science, just as we have given up hope of intuitively satisfying explanations in quantum mechanics.

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[17] It has been suggested that the the feelSpace belt could provide a qualitatively new perceptual experience [42]. However, the first person reports suggest that subjects' existing sense of space, location and landmarks was expanded and made more accurate, not that an entirely novel conscious sensation was created.

[18] This technology is being developed by Soterix: `http://soterixmedical.com/hd-tdcs`. The spatial resolution would probably have to be improved before it could be used for sensory substitution.

[19] David Gamez, 'The Hard and the Real Mind Body Problem', unpublished. Available at: `http://www.davidgamez.eu/papers/Gamez_MindBodyProblem.pdf`

Further research is also needed to determine whether *all* sensory contingency patterns are correlated with conscious sensations[20] and why some senses are richer and more vivid than others.[21] Finally, the hypotheses put forward in this article could help us to develop a better understanding of the conscious contents of infants, animals and artificial systems, whose sensory and sensorimotor contingencies are very different from our own. It could also help us to address some of the limitations of the current work on the neural correlates of consciousness that were identified by Noë and Thompson [45].

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[20] Humans might have a vomeronasal organ whose sensory contingencies are not correlated with conscious sensations [4, 44].

[21] The resolution of the different senses would be one place to look for an explanation.

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