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A Methodological Molyneux Question: Sensory Substitution, Plasticity and the Unification of Perceptual Theory

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Abstract

Since 1692, Molyneux's question to John Locke has been a focus for the discussion of perception in philosophy and psychology. In this chapter we introduce a methodological question inspired by the Molyneux problem. Can a conceptual framework developed to theorise one sense modality generalise to other modalities? Previous philosophical accounts of the senses have assumed that the presence in perception of an external spatial field, or of bodily awareness, is a stable characteristic of sensory modalities, the former being associated with vision, the latter with touch (Martin 1992; O'Shaugnessy 1989). From this, Martin (1992) argues against the possibility of a general theory of perception. However, findings of the plasticity of neural systems underlying sensory performance are a challenge to this assumption. Haptic awareness can become more "spatial" and less "corporeal" following the experience of optically driven touch stimulation in Tactile-Visual Sensory Substitution (TVSS). This removes one obstacle to a positive response to the MMQ regarding spatial perception. Yet neuroplasticity is not the whole story behind sensory substitution. We argue that the inherent similarity of certain visual and haptic spatial functions makes these more "substitutable" than others, and that it is valuable to apply a unified approach to these functions.

1. Introducing the Methodological Molyneux Question

Superficially, vision and touch could not seem more different. If vision shows us distant horizons, touch is limited to the boundaries of our bodies. Whereas vision is synoptic, a tactile picture of the world is built up through a laborious and methodical process of manual exploration. With the oft-noted assumption of visuocentrism in Western philosophy (e.g. Jay 1994, Rorty 1979), visual perception has been esteemed the paragon of objectivity, and touch of subjectivity (Jonas 1954). Such well-worn conceits suggest the pre-eminence of sight in the perception of space and in the apprehension of objects within it.

As we have argued elsewhere, the philosophy of perception has much to benefit from concentrating on commonalities between vision and touch (Paterson 2007, Paterson Forthcoming, Chirimuuta 2011, Chirimuuta Forthcoming), and one strand of debate stretching back to the original Molyneux question[1] certainly has aimed, as it were, to get a grip on the possible overlap of the visual and tactile, at least in terms of geometric concepts. Simply put, the question asks: if someone born without sight, but who had had direct tactile experience of a solid cube and a sphere, were suddenly able to see, would they be able to tell the objects apart by sight alone without touching them? (For further philosophical treatments see e.g. Morgan 1977; Evans 1985; Gallagher 2005; Dagenaar 1996; Paterson 2006; Paterson Forthcoming. For a very recent empirical approach, see Held et al 2011).

Subsequent philosophical discussion between Locke and Berkeley, and later figures such as Reid, pivoted on the possibility of a level of sensory abstraction before perceptions of objects become modality specific (Riskin 2002; Paterson Forthcoming). In this vein, one of Berkeley's stated tasks in *New Theory of Vision* was "to consider the difference there is betwixt the ideas of sight and touch, and whether there be any idea common to both

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[1] First formulated in a letter to Locke in 1688 that was ignored, William Molyneux posed the question to John Locke for a second time, following the publication of the first edition of Locke's celebrated *An Essay Concerning Human Understanding* of 1690, and subsequently incorporated into the 1692 edition.

senses" (1709 §1). Evans (1985) presents his summary and solution of the Molyneux problem as a lesson in dealing with the senses in more fine-grained bodily terms, considering the integration of vision with other bodily perceptions and sensations including audition and kinaesthesia. Evans dismissed psychological interpretations of the problem through Lotze (1885) and latterly Von Senden (1932/1960) which denied that the blind have any concept of space whatsoever. Even without sight there is, for the blind subject, the possibility of the formation of "simultaneous perceptual representations of his [*sic*] vicinity" writes Evans (1985:382), whether this occurs through acoustics, touch, or any combination of bodily movement and sensation.

Moreover, the dominance of vision in thought concerning the senses has frequently been noted and sometimes lamented (in philosophy e.g. Jay 1994; Noë 2004; in perceptual psychology e.g. Katz 1925/1989 and Gibson 1966; and in the social sciences, e.g. Csordas 1994, Howes 2003, Paterson 2009). Arguments in the philosophy of perception which restrict attention to sight risk not only monotony, but worse, potentially invalid generalisation to all senses of proposals holding only for vision. Yet even if a visuocentric stance were dropped, and philosophers were to use examples from touch, audition or smell to illustrate their theories, the question would still arise as to whether it is valid to extend the conclusions back to vision. It may be that we can have no general theory of the senses, only modality specific accounts[2]. Or it may be that, at some broad level of abstraction, an approach to the senses can be general, but solutions to specific problems must be modality specific. The issue of whether a conceptual framework developed to theorise one sense modality generalises to other modalities is raised by our *Methodological Molyneux Question* (MMQ). In this chapter we offer a preliminary response, with the expectation that progress can be made in future interdisciplinary work.

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[2] It pays to clarify terminology at this stage. By *general* theory of the senses, we mean one which is *non*-modal, one which is not dependent on the peculiarity of any one modality for its explanatory impact or intuitive appeal. This is related to – but not to be confused with – questions over *cross*-modality (the extent to which modalities interact with each other); *meta*-modality (the idea that brain areas are specialized to process certain types of information, which are better delivered by some modalities over others, but not exclusive to any modality (Pascual-Leone & Hamilton, 2001; Pascual-Leone et al 2006)) and the possibility of *non*-modal representations of geometric shape, as traditionally conceived in the Molyneux debate.

We restrict our attention to vision and touch here because the overt differences between these modalities present the most obvious obstacle to a positive response to the MMQ. A successful programme for unifying theories of vision and touch is grounds for optimism that the challenges presented by other modalities may be similarly overcome. Another reason for concentrating on these two modalities in particular is that a body of philosophical and empirical work already exists which analyses their similarities and differences, especially with respect to spatial reference frames, the coding of spatial properties, and the geometric concepts to be derived from them. This means we are not starting from scratch. We begin with M. G. F. Martin's (1992) description of a contrast between spatial reference frames employed in vision and touch, and his negative conclusion regarding the Methodological Molyneux Question. We argue that his rejection of the possibility of a common account of these senses is too dismissive, relying on two assumptions that are incompatible with what is known about the complexities of spatial perception in vision and touch. Martin's treatment assumes firstly that any difference between vision and touch is fixed, and secondly that these modalities do not present a variety of forms of spatial representation. In sections 2 and 3 we present case studies of sensory substitution and Braille that undermine Martin's account. We note that even though the technology of sensory substitution is promising, it is clear that visual and tactile modalities are not ultimately unified or fully substitutable through TVSS. Given significant findings of disunity within modalities, we observe that some functionally defined visual submodalities do share common features with certain tactile submodalities. It is these commonalities that, along with neuroplasticity, allow for substitution of perceptual functions. So while it is tempting to assume that the only way there can be an affirmative answer to the MMQ is if there is some arena in which somehow all sense modalities are unified, this notion of functional substitution leaves open the possibility of a more unified account, without any strong thesis of full sensory interchangeability.

In posing the Methodological Molyneux Question, we seek to initiate future investigation into the possibility of a philosophical framework which is not modality specific in its characterisation of what perception is and how it works. One clear motivation for this question is the growing appreciation of the importance of cross-modal spatial attention (see Spence and Driver 2004) and cross-modal sensations, which cannot be understood within modality specific theories, such as bodily sensations that lie outside of the Aristotelian model of the five distinct or extant senses (e.g. Kemp and Fletcher 1993; Spelke 1998; Streri and Gentaz 2004, Ganson and Ganson 2010). Moreover, this work is clearly complementary to the ongoing debate over how the sense modalities should be categorised and defined (e.g. Keeley 2002, 2009; Noë 2004, MacPherson 2011). Much empirical work suggests that each modality is more complex and nonunified than our phenomenology suggests[3]. So it pays to ask what other routes remain open for the theoretical re-integration of the senses.

Martin's Caution Regarding a Unitary Theory of the Senses

Space does not allow a full response to the MMQ in this chapter. Rather, we focus our efforts on removing certain obstacles to a positive response, targeting Michael Martin's swift rejection of any general accounts of visual and tactile modalities. One of the supposed key differences between vision and touch concerns how spatial relations are or are not conveyed (see Millar (2006) for useful overview). Many discussions have focussed on the spatial competencies of the blind. For example, von Senden (1932) went so far as to argue that the congenitally blind lack a concept of space. Révèsz (1950) observed the performance of blind subjects in spatial tasks such as distance estimation and concluded that touch relies wholly on a body-centred ("egocentric") reference frame, whereas visual reference frames utilise external ("allocentric") coordinates.

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[3] To take the one example of touch, it is not simply a skin-sense but constituted by reafferent feedback at dermal and epidermal levels dealing with pressure (mechanoceptors), temperature (thermoreceptors), along with nerve endings in the muscles dealing with position (proprioceptors) and pain (nociceptors) (Paterson 2007). Below we use the term "haptics" following Gibson (1966) as a sensory subsystem combining cutaneous pressure sensitivity plus kinesthesis, the sensitivity to muscular movement and load. Note that Fulkerson (2011) argues against the idea that the different functional sub-modalities of touch are so disunified as to warrant consideration as separate modalities. His case is not problematic for our argument because we posit only that there are functionally dissociable sub-modalities within the touch modality, concurring with Fulkerson (2011:498) that equivalent dissociations also occur within other modalities including vision.

While Millar (2006) presents evidence that external reference cues can indeed be used in haptic tasks, Révèsz's notion of a fundamental difference is the view more in tune with Martin's (1992) approach. "Sight and Touch" is one of the minority of works in the philosophy of perception that grapples directly with touch[4]. From the phenomenology of these modalities Martin argues that there is a "structural difference between sight and touch" (p.197). While vision locates objects in an external field, Martin doubts whether touch, which relies on other somatic factors, involves a comparable field: "the visual field plays a role in sight which is not played by any sense field in touch. Touch is dependent on bodily awareness and if, or where, that involves a sense field, it does so in a strikingly different way from that in which visual experience involves the visual field" (p.197). Martin finds the root of the difference in his contention that while the visual field's display of objects is located within it, objects of touch are felt only as impinging on the skin[5], and therefore not contained by any corporeal sense field:

> The spatial character of bodily awareness will force on us an alternative conception of spatial experience. Central to it will be this contrast between the sense of that which falls within the limits of experience and things feeling to be within a space which extends beyond those limits. (p.203)

By positing such a distinction between the spatial characters of incommensurable sensory fields, Martin reaffirms Révèsz's assumption that the visual field is a properly spatial field, involving distance, whereas touch and bodily awareness, insofar as it might constitute a field in itself, is one of contact and proximity, though one which presents objects as extending past the dermal limit. Later, Martin is left "sceptical as to whether

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[4] But see also, Berkeley 1709, Merleau-Ponty 1949/1992, O'Shaugnessy 1989, Smith 2002, Fulkerson this volume.

[5] See Fulkerson (this volume) for the argument that extends beyond the limits of the body, in cases where probes and tools are actively manipulated by the subject. However, as (Millar 2006:28) describes, views like Martin's are more typical: "The traditional division of sense modalities into 'proximal' and 'distal' senses has had a considerable influence on the view that visuo-spatial concepts differ radically from spatial concepts derived from touch. Touch has typically been considered a proximal sense, because the stimuli arise from direct contact of objects with the body. That seems to be in complete contrast to the distal senses, especially vision, in which stimuli arise from distant objects[…] However, as we shall see, this seemingly obvious common sense classification is not actually useful when trying to determine the relation of spatial processes to modality effects." Note that Martin's refinement of the proximal-distal modality distinction does (rightly) consider that touch allows us to perceive objects as lying in space beyond the body, and so is not confined representation of mere dermal stimulation.

one can give one general theory of what perception is, and in particular what it is to perceive the spatial properties of objects" (p.211) and concludes that "there is no reason to think that any theory adequate to one sense should be adequate to all." (p.215).

It would seem that Martin is trenchant in his dismissal of our Methodological Molyneux Question, but we believe that a more nuanced appraisal is needed, contesting two assumptions that lie behind his move from observation of certain differences between vision and touch to his general negative conclusion:

A. Each sensory system is fixed in the way it represents objects in space.
B. Each sensory system is uniform in its representation of objects in space, not allowing for functionally specialised subsystems that utilise different kinds of spatial reference frames.

Firstly, we challenge assumption (A) by appeal to a case study on sensory substitution. Sensory substitution is only possible because our brain architecture allows for alteration of the way the substituting modality represents objects in space, such that it takes on some characteristics of the substituted modality. This can only occur because of the underlying phenomenon of neuroplasticity which allows for reorganisation of sensory pathways, even in adulthood (for recent reviews see Pascual-Leone et al 2005, Bubic et al. 2005). Martin's account does not consider the possibility of a subject developing a tactile sense field that more greatly resembles a visual field, and as such is consistent with the now outdated tradition which posits that sensory systems remain fixed after development (Wiesel and Hubel 1963, 1965).

Secondly, the assumption of uniformity (B) is undermined by the consideration of parallel processing within sensory systems, which appears to map onto functional differences. The most well known cases of within-modality differentiation are the "what vs. where" streams in vision (Mishkin et al 1983) characterised by Milner and Goodale (1995) as 'vision for conscious representation' versus 'vision for action'. As we will see in section 3, sensory substitution also relies on a functional heterogeneity within sensory modalities, so that even if two modalities are rather different on first view, particular functions of their sub-modalities can still be readily substitutable. We illustrate this idea with a case study on Braille, which we term a ‘functional substitution’.

2. Sensory Substitutions

Martin’s strong hypothesis is that we cannot give a general account of what it is to perceive the spatial properties of objects. His point is that the geometric curvature of a rubber ball, for example, is *seen* in the context of a visual field, and *felt* as a type of impression on the skin, an impingement on the bodily contour of an object that resides in a space beyond the body’s sense field. One tacit assumption (A) is that these contrasting characteristics of the modalities are fixed. But if under certain circumstances the phenomenology of touch can be released from its entanglement with bodily sensation, becoming more distal and vision-like, then Martin’s point is undermined. In other words, the changeability of sensory systems, and the variety of perceptions they bring about, means that Martin cannot have said the final word on visual or tactile spatial perception. An appropriate place to look for such counter-evidence is through a case study of sensory substitution.

The Case of the “Seeing” Tongue

The key goal of sensory substitution systems is that, in the absence of one modality, another may be repurposed to provide equivalent information. Sensory substitution technologies require fast perceptual learning and, over the long term, substantial cortical remapping. There is a range of such sensory substitution systems, including tactile-audio and tactile-vestibular substitution, but the system most relevant to our meta-Molyneux discussion is tactile-visual sensory substitution (TVSS), as it foregrounds the translation between vision and touch, especially when performing spatial tasks. As the pioneer of TVSS from the 1960s until his death in 2006, Paul Bach-Y-Rita, explains: “In a tactile sensory substitution approach, a sensory system previously virtually restricted to contact information must mediate three-dimensional spatial information and integrate spatial cues originating at a distance” (1972:66).

The first devices were largely mechanical, such as the hulking research device built in 1968 that translated a tripod-based low-resolution video feed into patterns of pressure on the skin. Because of the physical size of the tactile array, a 20x20 grid spread over ten square inches, the trunk of the body was the only practicable area (Bach-y-Rita 1972:3). Despite such low resolution, with periods of training congenitally blind subjects could actually discern basic shapes and letters. The transition to a more portable system necessitated a shift from mechanical to electrical systems, and in 1971 a prototype of the Smith-Kettlewell Portable Electrical Stimulation System was demonstrated with blind subjects using a head-mounted camera but a lower resolution 8x8 array of brass discs held in a plastic grid pressed to the abdomen. An unforeseen outcome of this increased mobility was in the new potential for the subject to interact with the environment, so that picking up a telephone for example exploited a “hand-sensor” coordination that was technically impossible before. Proceeding versions of these devices unsurprisingly decreased in physical size while increasing the resolution of the vibrotactile array and were subsequently developed for commercial use, marketed in the early 1990s as the VideoTact™ for $45,000 (Visell 2009).

More recently a tongue-based variant known colloquially as the “lollipop” has been tested experimentally and even featured in the media. Developed initially by Bach-y-Rita and his company Wicab Inc. from 1998, the lollipop is a highly portable Tongue Display Unit (TDU) to be marketed as the BrainPort™. A tiny videocamera mounted within spectacles feeds directly into a flexible 25x25 electrode array on the tongue, where the patterns of electrical stimulation reportedly feel like champagne bubbles popping. This system outperforms earlier versions of TVSS because the tongue is smaller and more sensitive than the back or abdomen, and saliva in the mouth enhances the electrolytic environment, increasing conductivity (Bach-y-Rita et al. 1998).

The technology has proved successful for seeing shapes, letters, reading words, and enhancing mobility and spatial awareness without vision. Media coverage and news footage of blind subjects playing games of noughts and crosses, throwing darts at dartboards, and navigating cluttered courses (BrainPort website, *Daily Telegraph*, Sampaio et al 2001, Ptito et al 2005) reveal that the specifications of resolution and refresh rate for the tactile array are good enough to make the device useful in practical tasks.

The Brainport™ and earlier incarnations of TVSS have already attracted much philosophical interest. Morgan (1977) for example argues that the existence of TVSS implies a positive answer to Molyneux's question. Heil (1983), Hurley and Noë (2003) and Noë (2004) all describe TVSS as endowing a kind of seeing (see Prinz (2006) for opposing view). One of the reasons for claiming that TVSS enables one to see is the 'looming' effect of a camera zoom. If the experimenter makes the TVSS camera zoom into an object, the sudden expansion of the object causes subjects to flinch as if the object is hurtling towards them (Bach-y-Rita 1972:98). This zoom-like effect relies on a characteristically visual stimulus, the expansion of optic flow (Gibson 1979). We emphasise that TVSS enables the modality of touch to respond to spatial cues normally only available to vision, while we remain non-committal as to whether these particular functional equivalences should rightly be described as sight (hence the scare quotes around the '"seeing" tongue'). Indeed, the debate over whether TVSS perception is seeing is orthogonal to the concerns of this chapter.

An important observation about TVSS is that its benefits are not instantaneous. Switching on the machinery does not immediately endow the subject with this new perceptual capacity. Instead, there is a steady learning process through which the TVSS system becomes a useful means of performing certain perceptual operations (Bach-y-Rita 1972, Sampaio et al 2001; Ptito et al 2005, Bubic et al 2010). The learning rates for different tasks vary. While target detection and spatial orientation are almost immediate, discrimination of horizontal and vertical lines and direction of movement takes some practice. The fast recognition of ordinary objects usually takes 10 hours of learning (Lenay et al 2003:279). A crucial precondition for learning to take place is that the subject must be allowed to manipulate the camera and actively engage with the sequence of image capturing. A series of static forms on the tactile matrix does not facilitate learning, and feedback on discriminatory performance is essential (Sampaio 1995).

Note also that following this process of adaptation TVSS stimulation is not felt as if on the skin, as a kind of bodily sensation, but comes to be "projected" into a reference frame external to the immediate point of vibrotactile contact with the device. The tactile stimulation which conveys information about distal objects is readily distinguished from local irritations on the skin due to the electrode matrix. As Lenay et al. write, "Initially, the subject only feels a succession of stimulations on the skin. But after the learning process […] the subject ends up neglecting these tactile sensations, and is aware only of stable objects at a distance, "out there" in front of him [*sic*]" (2003:279).

Thus TVSS users perceive objects as residing in a space removed from them which, in this regard, is analogous to the visual field. This observation contrasts with Martin's hypothesis that objects felt by touch must appear as impingements on the bodily contour, but not contained within the sense field of that modality. As Lenay et al. (2003:282) continue,

> the subject appears to ignore the position of the tactile stimulations (unless he [*sic*] consciously refocuses his attention on that aspect of the situation) to the benefit of an apprehension of the spatial position of the light source. Conversely, artificial stimuli produced independently of the movement of the finger on which the photoelectric cell is placed are not associated with a distal perception, but continue to be perceived proximally at the level of the skin. Similarly, if the movements [of the perceiver] cease, the distal spatial perception disappears.

These authors describe an entirely pared-down experimental system, using just a single photodiode on the index finger of one hand and a vibrator on the index finger of the other. Once the subject experiences the correlations between exploratory movement, object presence and tactile stimulation, the vibrations induce perception of a distal object, even when the position of the vibrator on the hand is altered. That the effect requires only a TVSS of a very minimal sort is notable, as it shows that spatial perception of objects within a field comparable to a visual field can arise with sensory capacities that otherwise bear little resemblance to vision.

We now consider what happens during the periods of acclimatization. The learning required for TVSS use is understood to be correlated with structural and physiological changes in the brain, including the visual cortex. In one neuroimaging study Ptito, Moesgaard and Gjedde (2005) trained 11 early blind participants to discriminate the orientation of a target using the 12x12 electrode TDU (tongue display unit). After one hour of practise the blind participants showed significantly increased activity in the visual cortex when performing the task, activity not found in the PET scans prior to training. In other words, learning to use TVSS involved the recruitment of new sensory areas of the brain that were not activated initially. It is interesting to compare this study with the longstanding observation that Braille reading involves the recruitment of the visual cortex, even in bindfolded sighted participants undergoing prolonged visual deprivation (Kauffman et al 2002, Pascual-Leone et al 2006).

Importance of Neuroplasticity

Ptito et al's (2005) imaging results are unsurprising. Bach-y-Rita and Kercel (2003) state: "Sensory substitution is […] only possible because of brain plasticity". It is worth pausing here to consider why this is so. The fact that the brain is "plastic" throughout its lifespan is increasingly recognized to be key to understanding many of its functions, not only in memory and learning, but also for perceptual and cognitive processes, and recovery after injury. Profound changes in the organization of sensory systems occur not only after contact with substitution devices but also as a result of sensory loss or temporary sensory deprivation (Büchel, C. *et al* 1998, Kauffman et al 2002, Pascual-Leone et al 2006, Merabet and Pascual-Leone 2010, Bubic et al 2010). It is often noted that the brain of non-sighted individuals "compensates" for the loss by recruiting visual areas of the brain in tactile and auditory tasks, and the extent of compensation does indeed correlate with enhanced behavioural performance. For example, certain blind individuals such as Daniel Kish have learnt to navigate through crowded areas using an echolocation technique, making click noises with the tongue and attending to the echoes in order to sense approaching obstacles. Thaler, Arnott and Goodale (2011) have published fMRI data on two subjects who lost sight either in childhood or adolescence indicating that the primary visual cortex is involved in the utilization of echo information for detecting objects in space. In other words, the self-motivated learning of echolocation has caused the visual cortex to become involved in a non-visual spatial task.

Neuroplasticity can involve changes in the number and strength of synaptic connections, metabolic changes, and even growth of new neurons (*neurogenesis*) in the adult brain. What is essential for the effective operation of TVSS is either the growth or reinforcement of peripheral connections from the substituting modality to the central brain areas that typically receive information from the substituted modality[6]. This allows for the substituting sense to receive stimulation in a format which is unusual for that modality – such as the optic flow information in TVSS – and for that stimulus to be interpreted in an appropriate way, in this example, as a 'looming' object.

Plasticity also occurs in motor areas of the brain, regions involved in orchestrating the movements of eyes and hands (Ptito et al 2005). As we have seen, practice in controlling the TVSS camera is crucial to developing proficiency, and this is because perception is at least in part a sensory-motor activity (Findlay and Gilchrist 2003). So for effective use of TVSS the subject must learn a pattern of movements that optimise the capture of visual information and these must become automatic through long-term structural changes in the brain.

We emphasise that the plasticity observed following TVSS is not inherently different from neuroplasticity in other contexts, such as normal development, skill learning and compensation following brain injury or sensory deprivation (for survey, see Shaw and McEachern 2001). TVSS consequently piggybacks on the pre-existing tendency of the nervous system to reorganise itself in response to changing external stimulation and internal conditions. So even though one might object that we appeal to a sensory system in a technologically modified state in our case against Martin, and that this is irrelevant to discussion of the nature of the sense, our response is that the argument we employ does not depend on TVSS *per se,* but on the very possibility of neuroplasticity. And this plasticity is also evidenced in other cases of perceptual learning just noted.

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[6] The choice is between growth and reinforcement of connections is not exclusive, however.

We can now recapitulate the case against assumption (A), that the sensory modalities are fixed in the way they represent objects in space. When the sense of touch is presented with optical stimuli, and trained to respond to this new type of information, new connections are utilised, linking areas of the brain involved in touch and those normally involved in vision. A consequence is that the touch modality becomes more vision-like, especially in its representation of the spatial location of objects at a distance from the body. Just as a visual image is not felt as a local irritation of the retina, a TVSS image is not felt as a stimulation of the skin. The sense of touch need not literally feel in touch with the objects it perceives. Contra Martin's idea of incommensurate sensory-spatial fields, the sense usually characterised as proximal can indeed become distal.

Overstating the TVSS Case

At this point it might be objected that even in normal touch, perceptions are not felt as local irritations of the skin. In an oft-cited paper on active touch, Gibson (1962) describes the key role of purposeful movement when the sense of touch is used for gathering information about the shape of objects. When subjects were engaged in such "active touch" tasks they were unable to report the flux of sensations on the skin, only the rigid edges of the object felt. He states: "One perceives the object-form but not the skin-form. The latter is, in fact, continually changing as the fingers move in various ways. It is almost completely unreportable, whereas the pattern of physical corners and edges seems to emerge in experience" (Gibson 1962:482). In active touch Martin's proposed body-field is transparent, and the perception lands firmly on the external object. Gibson contrasts these reports with his subjects' observations of passive touch, cases where the experimenter induces the same tactile sensations as would be caused by the subject's manual exploration. In those cases the cutaneous events become distinct to the subject as something happening to the body surface.

From this Gibson concludes that there is a mode of touching that is vision-like. He observes: "vision and touch have nothing in common *only when they are conceived as channels for pure and meaningless sensory data*. When they are conceived instead as channels for information-pickup, having active and exploratory sense organs, they have much in common" Gibson (1962:490; original emphasis). So even in sighted subjects and without technological intervention, there is flexibility in whether tactile sensations are felt as patterns of pressure on the skin or contours of external objects, depending on whether the subject is involved in an active perceptual task.

So we must be careful not to overstate the TVSS case. TVSS furnishes us with a quick rebuttal of one obstacle to a general account of perceptual systems, such that we need no longer assume that there is a fundamental, insurmountable difference between the way the modalities of vision and touch represent objects in space. This is because, as we have seen, touch can readily be repurposed to utilise visual information, and there is imaging evidence that cortical plasticity is involved in this process. Yet the discussion of active touch gives us reason to think that vision and touch might not be so different to begin with. We argue in the proceeding section that the successful functioning of TVSS is also due to the inherent complexity of the touch modality in how it represents objects in space. There is more to the story than just cross-modal plasticity.

On the other hand, our case study of TVSS does not by any means demonstrate that vision and touch are completely substitutable, and this leaves room for anyone arguing for a negative response to the MMQ to posit that there is an insurmountable difference between vision and touch other than the distal-cutaneous distinction in spatial perception which we have addressed in this section. Interestingly, some rather strong claims have been made for TVSS as evidencing the substitutability of vision by machine-aided touch. So before moving on to the next section, it is worth pausing briefly to evaluate some of these claims and show why our final case against Martin cannot be made from TVSS alone.

Although somewhat subject to marketing hyperbole, the trademarking and use of the term "Brainport" are significant, heralding a new kind of technology that bypasses peripheral sensory limitations. Amongst the Wicab company's online promotional material, a short video includes the line: "your brain is what really sees, not your eyes." The implication is that this technology creates a new portal into the brain, bypassing the diseased or damaged eye and optic nerves, thus allowing the subject to see again. Such taglines imply that the process of seeing is straightforwardly a case of directing optical information to the skin through technological means, from where it will be channelled to the brain. Because of neural plasticity, the brain can use information from the tongue as if it came from the eye, resulting in sensory interchange.

There are numerous reasons to be sceptical about such claims for the power of TVSS. A primary issue is that cortical reorganisation is limited in adults. Even if a complete rewiring of somatosensory connections to the visual cortex might be possible for the very immature brain, this is beyond the capability of the adult brain. In their review Bavelier and Neville (2002:446) revisit Hubel and Wiesel's idea of a critical period for the forging of useful connections to sensory cortices. Although the physiology is more complex than Hubel and Wiesel envisaged, with much plasticity occurring beyond critical periods, it is still true to say that the immature brain has a degree of plasticity that is lost to the adult one. Accordingly Bubic et al (2010:368) recommend introduction to sensory substitution devices as early as possible in childhood to maximise the potential benefit. To reiterate, if TVSS could demonstrate that vision and touch were completely interchangeable, even in adulthood, then the case against Martin might be closed. This is not so, but we have indeed seen that the spatial 'fields' of vision and touch are subject to alteration with TVSS use, and this challenges Martin's assumption (A) of a fixed difference between these modalities with respect to spatial awareness. In the next section we address the other assumption (B), that each modality only uses one type of spatial representation.

3. Functional Substitution

At the end of section 2 we emphasised that TVSS does not in itself support any strong claims that vision and touch are interchangeable modalities. Consequently, there remains room for someone arguing against a positive answer to the MMQ to posit an irreconcilable difference in the spatial representation afforded by vision and by touch, other than the distal-cutaneous distinction that was challenged above. It is reasonable to think that the performance of TVSS is restricted by the nature of the sensory systems involved, such that they are never fully substitutable. However, it would be too hasty to concede immediately that no general account of them could ever be formulated. Our task in this section is to question what obstacles to sensory substitution arise from the architecture of vision and touch but also, conversely, to explore how certain kinds of substitution are made possible due to pre-existing commonalities across these modalities. In this section we introduce the weaker notion of 'functional substitution', and show that even this has positive implications for the MMQ. In other words, there need only be a 'weak' functional equivalence rather than a full blown 'strong' substitution to undermine both obstacles to a unified sensory philosophy.

One factor limiting sensory substitution is the enormous difference in the spatial resolution of pressure receptors on the skin and photoreceptors in the eye. So even if technological advances deliver TDUs with a far higher resolution than the current 25x25 array available, the device will meet the inherent limits of vibrotactile discrimination and the density of nerve endings in the associated body parts. Regardless of the possibilities of cortical reorganisation, the number and distribution of cutaneous nerve endings is not subject to neuroplasticity. Bach-y-Rita and Kercel (2003) argue that such low tactile resolution is not actually an obstacle to TVSS replacing sight, but this is the case only if one constrains the definition of sight to certain coarse discriminations or optically induced responses, such as the recognition of large projected shapes, or the ability to dodge a 'looming' object. The acuities attained through earlier incarnations of the "lollipop", as reported by Sampaio et al. (2001), are actually so poor that a person performing at this level would be classified as legally blind.

Another constraint is imposed by, as it were, the hardware of the body. As noted above, the subject's active control of the TVSS camera is a requirement for learning to interpret the vibrotactile patterns. Efficient manipulation of the camera is essential for strong perceptual performance, a sensorimotor skill that develops with prolonged use of TVSS. However, if the subject's viewpoint is controlled through directing the head-mounted eyeglass camera, this involves orienting the head in its entirety and will never be as fluid or rapid as the automatic and largely unconscious control of ocular movements. Saccades, the ballistic type of eye movement used for most tasks such as scanning scenes, examining objects and reading, are actually the fastest movements made by the human body. An adult engaged in a natural viewing task makes 3-5 saccades each second, and saccadic reaction times can be as short as 100 milliseconds (Fischer and Weber 1993), whereas the minimum reaction time for a manual response is more than twice as long at 250 milliseconds (Kirchner and Thorpe 2006). Against any assertion by the Brainport™ company, that it is the brain which sees rather than the eyes, the ocularmotor system performs an active – indeed, almost hyperactive – perceptual process that TVSS systems are unlikely to replicate in the near future.[7]

Nevertheless, we know that in some cases, according to certain functional measures such as shape and size discrimination, substitution is deemed successful. What makes it work in those cases, and according to what specific criteria of success? Is it simply the greater degree of neuroplasticity found in those sensory sub-systems? Or that certain functions or submodalities can be readily substituted because of the existence of corresponding functions in the substituting sense? We now concentrate on this last proposal, but note that plasticity is still crucial even for this limited form of substitution, evidenced by the training periods required. The idea we wish to convey is that these functionally-defined systems are channels or streams within which plasticity can most usefully occur in response to TVSS.

Such considerations will give us reason to reject (B), the assumption of the uniformity of individual modalities in their representation of objects in space. This assumption stood behind a negative thesis that there cannot be a general account of the senses. We describe how there is variety in the spatial reference frames employed by individual modalities. As we saw in the TVSS example, touch, as well as vision, may use object-centred (allocentric) rather than body-centred (egocentric) frames of reference for certain tasks,

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[7] Hurley (1998) and Noë (2004) have made much of the research on ocular-motor activity to ground the claim that perception is a kind of action, and that motor and sensory systems cannot actually be separated. However, these facts about ocularmotor control stand against their strong claims about TVSS being a kind of vision (Hurley and Noë 2003). Until camera control can even approach the precision and rapidity of normal ocular-motor control, TVSS enhanced touch will never be fully functionally equivalent to vision.

and in fact this is corroborated in the psychology literature (see Millar 2006, Klatzky 1998). Sensory substitution is possible because of such similarities across certain modalities, and can be thought of as expanding the repertoire of tasks for which touch uses object-centred representations. As we will see in the example below that employs minimal technological intervention, the kinds of reference frames available to a particular modality set out the parameters for successful substitution, and some possible explanations for this are discussed later. First, a brief account of an example of weak 'functional substitution' will set this up.

Lessons in Braille

The ideas developed in this section are best introduced by considering a very different kind of sensory aid – Braille. It is revealing to compare the technology of writing with sensory substitution technologies. Written scripts are means for efficiently converting aural phonemes into visual graphemes or pictograms. Braille, in turn, recodes the visual alphabet into manually perceptible sequences of characters. We refer to this as a 'functional substitution' (after Klatzky, personal communication) as opposed to a 'sensory substitution' because the substitution applies to the specific act of reading and is not a general correspondence between sense modalities. The transfer is possible because both visual and touch modalities are able to represent a sequence of small characters that are individuated by relatively subtle spatial details. These details rely on the consistent application of an allocentric reference frame for their disambiguation, e.g. the two slanted lines of a capital A, or top left dot of the Braille A.

In such cases it is useful to characterise the perceptual function non-modally, e.g. as the mapping of nearby objects in allocentric coordinates, or the precise localisation of lines or dots on a page. Still, one modality may be more capable in this task than another. As Kauffman et al. (2002) report, those sighted individuals who do learn Braille end up relying on visual rather than haptic recognition of the characters. But even if it is the case that visual input dominates when sight is intact, the reading function need not be thought of as necessarily visual, since when necessary touch can substitute for vision and perform the function. It is a function that is readily substituted for, even if the entire modality is not thereby substituted. This is another reason why we talk of Braille as a functional rather than simply a sensory substitution.

It is significant, however, that Braille signs are not simply Roman letters raised from a surface. In order to maximise the capacity of the haptic system, configurations of raised dots are used instead. For example, Loomis (1990) reported that the ability of blindfolded sighted subjects to identify raised letters and digits was poorer (40% accuracy) than their ability in recognising Braille characters (56% accuracy). This indicates that the difference in the way that spatial information is gathered by the haptic and visual systems is notable, affects discriminatory performance and is not readily overcome with training and the resultant brain plasticity.

Functional substitution is possible when a task – and potentially some brain region required for it – can be characterised non-modally, and when the substituted and substituting sense share some features in common regarding how they represent objects and space. However it is critical to acknowledge the variability within each modality in the tasks it performs, and the ways in which it performs them. We replace assumption (B), that each sense is monothematic or uniform in its representation of space, with a picture in which modalities contain within themselves numerous functional streams requiring different spatial reference frames, some of which may be similar to those of other modalities (see figure 1).

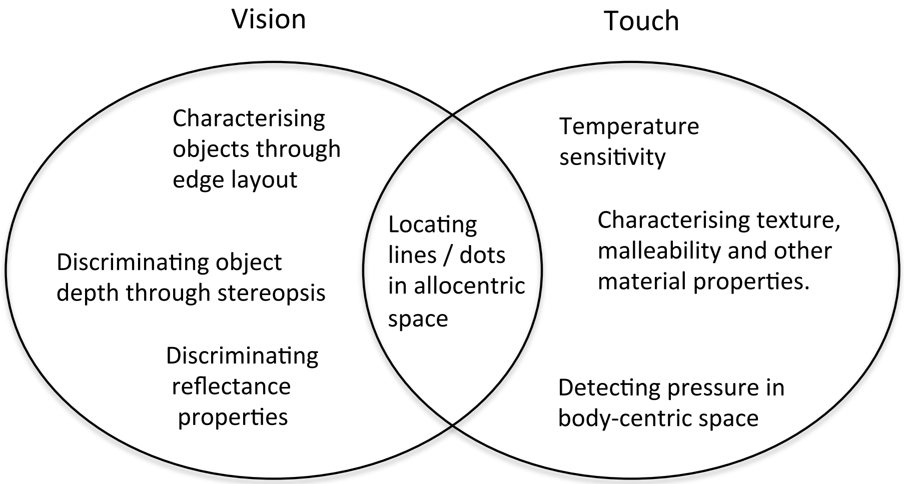

Figure 1: A representative, but not exhaustive depiction of the functions of visual and tactile modalities. Where functions overlap, the potential for substitution increases.

Another surprising finding consistent with our picture of partially overlapping functional commonalities is the difficulty in recognising a two dimensional raised line drawing of an everyday object by touch alone, a kind of recognition that we do effortlessly and instantaneously by sight (Lederman et al 1990). Blindfolded subjects are correct only on 34% of trials when given 2 minutes of exploration time. Subjects achieved up to 100% accuracy at recognising *actual* objects haptically within just 1-2 seconds (Klatzky, Lederman, Metzger 1985). In that case material cues were present, such as the texture of the surface, and no 3D to 2D projection was involved. Klatzky & Lederman declare that "haptic object identification cannot rely virtually entirely on information about the spatial layout of edges, as appears to be the case in vision", and that "material properties were shown to be more available than spatially coded properties under haptic exploration" (2003:116). Put simply, a two-dimensional projection of a three-dimensional object is decoded by the visual system with ease, whereas the haptic system struggles to make sense of this kind of spatial information. Yet it does not follow that the haptic system is deficient in all kinds of spatial tasks.

Because neuroanatomical knowledge is incomplete, we can only speculate about the extent to which certain cortical areas are modality-specific, cross-modal or non-modal. Whem the ‘input’ for a task is provided by one sensory modality or another, the ‘processing’ need not be served by a modality-specific brain region. What we do know is that the anatomical and physiological picture is complex, with neurons and circuits having different levels of task and modality specialisation, and all contributing to the execution of these perceptual functions. For instance Millar (2006:31) writes:

> [T]he specialized sensory, visual, tactile, and movement analyses are not only processed further in dedicated visual, tactile, and motor areas of the brain. Inputs from these areas also converge in multiple, distributed brain areas that are involved in diverse spatial tasks.

Braille in fact provides an excellent example of the non-specialised and distributed nature of sensory and spatial tasks. In oft-cited work, blind Braille experts show activity in areas of the visual cortex during reading (Cohen et al. 1997, Hamilton and Pascual-Leone 1998). Further studies provide evidence that this activity is functionally necessary and not merely epiphenomenenal. Braille readers receiving transcranial magnetic stimulation (TMS) to disrupt activity in the visual cortex find they are temporarily unable to distinguish the characters (Kupers et al. 2007). James et al. (2006) report that an extremely proficient Braille reader who suffered a stroke affecting visual cortex subsequently lost her ability. Now, while appropriation of the visual cortex for tactile processing was above taken as an indication of the power of neuroplasticity it is necessary to qualify this view. Pascual-Leone and colleagues present an alternative hypothesis, arguing that the visual cortex receives non-visual inputs even in sighted individuals, and that these are “unmasked” under conditions of visual deprivation:

> [A] sense-specific brain region like the ‘visual cortex’ may be visual only because we have sight and because the kinds of computations performed by the striate cortex are best suited for retinal, visual information. For example, we might postulate that the ‘visual cortex’ is involved in discriminating precise spatial relations of local, detail [*sic*] features of an object or scene, which might be more advantageously done using visual than other sensory modalities. However, in the face of visual deprivation or well-chosen, challenging tasks, the striate cortex may

> unmask its tactile and auditory inputs to implement its computational functions on the available nonvisual sensory information[8]. (Pascual-Leone et al. 2006:173)

In support of this view, these authors report that sighted people *can* learn to read Braille haptically, and visual cortical activity is observed, but only if they spend a week under conditions of complete visual deprivation and are provided ample training in Braille use (see also Kauffman et al 2002). Not only does this haptically-evoked visual activity appear rapidly, but it disappears even more rapidly, typically within 24 hours of the subjects' blindfolds being removed. The results suggest that the somatosensory input to the visual cortex exists already in the sighted, as there is insufficient time in the course of the experiment for entirely new neural pathways to grow. So, in support of a positive answer to the MMQ, the visual cortex can be thought of not only as a brain region that plastically adapts to receive tactile stimulation, but also one that is somewhat non-modal originally. This provides one reason to think of the functions served by visual cortex as suitable for general, rather than modality specific, analysis.

To sum up, the apparent substitutability of certain sensory functions is not due to unconstrained plasticity, but rather the plastic reinforcement of one aspect of the substituting modality (e.g. fine spatial discrimination in an external spatial reference frame) that was pre-existent but overshadowed by the substituted modality. This conclusion also gives us grounds to reject the assumption of the uniformity of each sensory modality with respect to spatial representation (B), which was the other reason for dismissing the possibility of a general account of perception. One cannot assert that there is an irreconcilable difference between vision and touch, *tout court*, if within each of these modalities there are various functional streams, some of which do comparable things haptically as are typically done visually. The most obvious counterevidence to (B) is the work showing that the touch modality uses external spatial frames (allocentric coordinates) for certain tasks, just as with vision, and is not restricted to a body-centred space as Martin assumes (see e.g. Millar 2006).

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[8] Also described as the "metamodal brain" hypothesis. See note 2 above.

4. Conclusions

In the last two sections we removed a pair of obstacles to a general account of the senses. But does the material covered in this chapter also provide us with resources for a positive case for unification? Well, the idea that certain functions are substitutable because of the similarity of operation across modalities, and the sharing of neural resources for these tasks (which is enhanced by brain plasticity, even in adults) gives grounds for a tentatively positive response to the MMQ. At this stage we clearly cannot claim to have a general account of all perceptual processes, including ones such as colour discrimination that are not mirrored in any modalities other than vision. However, for certain perceptual processes a general, non-modal description is arguably an improvement on a modality specific one. That is, for a set of sub-functions of touch that have more in common with certain visual functions than with other tactile ones, it makes sense to integrate the theoretical account with the visual cases rather than mix together some rather dissimilar processes all under the unified heading of "touch". Whether the accounts of all perceptual functions can ultimately be integrated is a question for another day. At least we have challenged some assumptions that might otherwise prevent us even enquiring.

Note that our tentatively positive response to the MMQ comes with an important caveat regarding the relevance of subpersonal neuroscientific data to a theory of perception which is traditionally pitched at the personal level. If there is evidence for general non-modal spatial processing, this suggests a positive answer only insofar as the senses can be theorised at the subpersonal, neurophysiological level. However, this does not necessarily translate into a positive response that would satisfy the requirements of a psychological or philosophical theory of perception because unity at the neural level clearly does not entail unity in any phenomenological aspects. Psychophysical experiments need to be performed in order to demonstrate that neural commonalities are mirrored in behaviour. Our examples of TVSS and Braille fulfil this requirement because they point to cortical activity that is not unique to one modality (e.g. visual cortex activity during TVSS or haptic discrimination tasks) but does indeed correlate with a subject's ability to perform equivalent tasks with different modalities.

We have argued that a general philosophical account of perception is not impossible. This chapter is, by necessity, an overview of a wide range of interlinked issues. A key question remaining is over what purpose any conceptual unification of the senses might serve. Indeed, there is much scope for future work looking specifically at different spatial tasks, and the detailed processes of Braille learning, tactile mapping and spatial navigation. It remains to be seen if this work can only proceed in a case by case basis, or if more general principles of non-modal function or cross-modal interaction are likely to emerge.

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