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Perception With Compensatory Devices: From Sensory Substitution to Sensorimotor Extension

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Abstract

Sensory substitution devices provide through an unusual sensory modality (the *substituting* modality, e.g., audition) access to features of the world that are normally accessed through another sensory modality (the *substituted* modality, e.g., vision). In this article, we address the question of which sensory modality the acquired perception belongs to. We have recourse to the four traditional criteria that have been used to define sensory modalities: sensory organ, stimuli, properties, and qualitative experience (Grice, 1962), to which we have added the criteria of behavioral equivalence (Morgan, 1977), dedication (Keeley, 2002), and sensorimotor equivalence (O'Regan & Noë, 2001). We discuss which of them are fulfilled by perception through sensory substitution devices and whether this favors the view that perception belongs to the substituting or to the substituted modality. Though the application of a number of criteria might be taken to point to the conclusion that perception with a sensory substitution device belongs to the substituted modality, we argue that the evidence leads to an alternative view on sensory substitution. According to this view, the experience after sensory substitution is a transformation, extension, or augmentation of our perceptual capacities, rather than being something equivalent or reducible to an already existing sensory modality. We develop this view by comparing sensory substitution devices to other ''mind-enhancing tools'' such as pen and paper, sketchpads, or calculators. An analysis of sensory substitution in terms of mind-enhancing tools unveils it as a thoroughly transforming perceptual experience and as giving rise to a novel form of perceptual interaction with the environment.

Keywords: Sensory substitution; Sensory modalities; Neural plasticity; Vision; Perceptual adaptation; Extended mind

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1. Introduction

Sensory substitution devices (SSDs) aim at replacing or assisting one or several functions of a deficient sensory modality by means of another sensory modality. To do so, these systems convert the stimuli normally accessed through one sensory modality (e.g., light when the *substituted* modality is vision) into stimuli accessible to another sensory modality (e.g., sounds when the *substituting* modality is audition). Since their inception in the 1960s various kinds of devices have been developed, tested, and shown to allow their users to behave to some degree as if they possessed the substituted sensory organ. For instance, thanks to visual-to-auditory or visual-to-tactile conversion systems, blind persons are able to localize and recognize objects in three-dimensional space (e.g., Auvray, Hanneton, & O'Regan, 2007a; Bach-y-Rita, Collins, Saunders, White, & Scadden, 1969).

Thus, the goal of SSDs is to re-establish a lost sense. But do they genuinely do so? In other words, one of the main questions raised by the use of SSDs is to which sensory modality the acquired perception belongs. Both the thesis that the acquired perception occurs in the substituting modality and the opposing thesis that the acquired perception occurs in the substituted modality have been defended. For example, Hurley and Noë (2003) (anticipated by Cole, 1990; Dennett, 1991; and O'Regan & Noë, 2001) have argued that when perceiving with a visual-to-tactile SSD, the experience swaps from the tactile to the visual modality. Hurley and Noë named this view the *deference* thesis, as the substituting modality defers to the substituted one. The opposite view has been proposed by Humphrey (1992), Keeley (2002), Block (2003), and Prinz (2006) who argued against a change in sensory modality. According to these authors, experience during the use of a visual-to-tactile substitution device remains essentially tactile. This view has been named, again after Hurley and Noë (2003), the *dominance* thesis, as according to this view the substituting modality dominates.

In this article, we raise the question of the sensory modality to which perception after sensory substitution belongs to and, subsequently, the broader issue of how sensory substitution should be understood. To do so, we apply the criteria that have been used to define and distinguish sensory modalities to the case of perception with an SSD. These criteria are those of sensory organ, stimuli, properties, qualitative experience (Grice, 1962), behavioral equivalence (Morgan, 1977), dedication (Keeley, 2002), and sensorimotor equivalence (Myin & O'Regan, 2009; O'Regan, Myin, & Noë, 2005; O'Regan & Noë, 2001). We discuss how different choices among these criteria lead to opposite positions in the debate on dominance versus deference. Building on the discussion of these criteria, we subsequently propose that we should move beyond the understanding of sensory substitution as occurring in either the substituting or the substituted modality. Specifically, we will reject the assumption, common to the dominance and the deference theses, that perception after sensory substitution can be conceived of as equivalent to perception in an already existing modality. Rather, we will argue that SSDs transform and extend our perceptual capacities. Following Auvray and her colleagues (Auvray et al., 2007a), Lenay and his colleagues (Lenay, Gapenne, Hanneton, Marque, & Genouëlle, 2003), and congruent with a broader view on cognitive enhancement through external devices (e.g., Clark, 2003; Menary, 2006, 2007), we thus propose that we should speak of sensory extension, supplementation, or transformation, rather than substitution.

We set out by reviewing the core findings in the field of sensory substitution by focusing on cases where the substituted modality is vision and the substituting modality is either touch or audition. Instead of attempting a complete coverage of the domain of sensory substitution for vision, we indicate those aspects that are relevant to the discussion of which sensory modality perception with SSDs belongs to.

2. Sensory substitution devices

The two main categories of systems that have been designed to compensate for the loss of vision are visual-to-tactile substitution devices that convert images into tactile stimuli and visual-to-auditory substitution devices that convert images into sounds.

2.1. Visual-to-tactile substitution devices

In most visual-to-tactile substitution devices, images captured by a video camera are translated into electrical or vibratory stimulation applied to the skin of a part of the body, such as the abdomen, the back, the fingertip, the forehead, or the tongue. For instance, a tactile device that has been commercialized is the electromechanical device ''Optacon,'' designed for reading. The Optacon consists of a large stylus used for scanning a printed text. A miniaturized camera placed on the top of the stylus scans the text, which is then converted into tactile vibrations on a matrix of vibrators upon which users place the fingers of their free hand. Research has shown that users can make use of visual-to-tactile substitution systems in tasks that would normally require vision, provided that they are granted active control over the substitution apparatus (e.g., Bach-y-Rita, 2002; although see Vega-Bermudez, Johnson, & Hsiao, 1991). In particular, research has demonstrated the ability of participants to succeed in localization tasks (Jansson, 1983; Lemaire, 1999), simple form recognition (Kaczmarek & Haase, 2003; Sampaio, Maris, & Bach-y-Rita, 2001), and reading (Bliss, Katcher, Rogers, & Shepard, 1970; Craig, 1981, 1983; Loomis, 1974, 1981). Some studies have also shown that users of such devices can perform perceptual judgments using perspective, parallax, looming and zooming, as well as depth estimates (Bach-y-Rita et al., 1969; Epstein, 1985). However, although various perceptual tasks can be accomplished with visual-to-tactile substitution devices, these systems are faced with certain limitations as they depend on the stimulation of a highly sensitive skin surface such as the tongue leading to problems of skin irritation or pain. Furthermore, the autonomy of portable versions of these devices is limited due to the substantive energy consumption of the tactile stimulators (Lenay et al., 2003).

2.2. Visual-to-auditory substitution devices

The other important field of research that aims at finding compensations for the loss of vision is the auditory substitution of vision. The use of the auditory system as the substituting modality offers many advantages. First, the human auditory system is able to deal with complex and rapidly changing sound patterns such as speech, and this even in a noisy environment (e.g., Hirsh, 1988). In addition, the auditory system has fine discrimination thresholds for intensity and frequency. Portable versions of visual-to-auditory conversion systems require only simple interfaces: headphones, a webcam, and a computer (Capelle, Trullemans, Arno, & Veraart, 1998). Finally, the technology of digital sound processing is very common and the generation of auditory stimuli requires little energy. The two main designs of visual-to-auditory substitution systems involve echolocation and image-to-sound conversion.

Echolocation devices are based on the same principles as sonar. An ultrasound source/receptor emits a stream of clicks and/or FM signals. Receptors use telemetry in order to determine the distance between the sound source and the distant object. This method consists of calculating the time taken by an ultrasonic signal to reach an object and to return by reflection to the generator. Signals are then converted into an audible frequency range and transmitted to users' ears via headphones, giving them an indication of the distance and direction of distant objects. For instance, distance can be coded by pitch and the horizontal position by inter-aural disparity (e.g., UltraSonic Torch, Sonic Glasses: Kay, 1964, 1985; Sonic Pathfinder: Heyes, 1984). These systems can be helpful for locomotion and the guiding of movements of blind persons (Heyes, 1984; Kay, 1964, 1985), and they can also provide information about the spatial layout of three-dimensional scenes (Hughes, 2001).

In systems of image-to-sound conversion, images captured by a camera are converted into sound and transmitted to users via headphones. The four main visual-to-auditory conversion systems that have been designed are the Voice developed by Meijer (1992), the PSVA (Prosthesis for Substitution of Vision by Audition) developed by Capelle and his colleagues (Capelle et al., 1998), the device developed by Cronly-Dillon and his colleagues (Cronly-Dillon, Persaud, & Blore, 2000; Cronly-Dillon, Persaud, & Gregory, 1999), and Vibe developed by Hanneton and his colleagues (Auvray, Hanneton, Lenay, & O'Regan, 2005). These four systems convert the vertical position of the registered pixels in the video image into different audio frequencies, with high-pitched sounds corresponding to upper locations and low-pitched sounds corresponding to lower locations in the image. These four systems convert the luminosity of the object into sound amplitude. With regard to the encoding of the horizontal position of objects, the Voice and the device developed by Cronly-Dillon use left-to-right time scanning to encode horizontal position, whereas Vibe uses inter-aural disparity only, and the PSVA uses a frequency mapping in addition to the one used for vertical position. More specifically, the frequency associated to each pixel increases from left to right and from bottom to top. Furthermore, in order to enhance the similarity with the human visual system, the receptor field of the PSVA has a higher resolution in the center of the picture. Studies that have been conducted with auditory devices have shown the possibility of object localization (Auvray et al., 2007a; Renier et al., 2005a) and form recognition (Arno et al., 1999; Arno et al., 2001 with the PSVA; Cronly-Dillon et al., 1999, 2000; Pollok, Schnitzler, Mierdorf, Stoerig, & Schnitzler, 2005 with the Voice). Interestingly, recent studies have also demonstrated the possibility of recreating visual illusions with the PSVA (Renier et al., 2005b).

Many other types of prosthesis have been designed, for example, to compensate for the loss of proprioceptive information due to a bilateral vestibular damage (e.g., Tyler, Danilov, & Bach-y-Rita, 2003), to compensate for the loss of tactile sensations due to leprosies (Bach-y-Rita, Tyler, & Kaczmarek, 2003), or else the absence of pain feelings (see Brand & Yancey, 1993). Thus, there are many possibilities to convert stimuli normally belonging to one sensory modality into stimuli handled by another sensory modality, and sensory substitution systems can take a broad variety of forms.

3. Which sensory modality does perception with an SSD belong to?

The possibility of having access to stimuli normally accessed through one sensory modality (light) by means of their conversion into stimuli accessible to another sensory modality (tactile vibrations) raises the question of whether perceiving with a visual-to-tactile conversion system remains tactile or whether it can be considered as being a genuine form of seeing. An answer to this question seems to require a definition of what constitutes a sensory modality and an account of what distinguishes the different sensory modalities. So far, the attempts made of providing a definition of sensory modalities remain controversial. However, there are a number of criteria that are relevant for characterizing the senses. In an early discussion on this topic, Grice (1962) proposed that four criteria allow for a distinction between the sensory modalities. Sensory modalities can be distinguished by the type of sensory organ involved in perception, the differences between the stimuli used in perception (e.g., vibrations in the air for audition, light for vision), the properties that perception provides access to (e.g., odors for smell, colors for vision), and the qualitative aspect of the perceptual experience. This list can be completed with three additional criteria that have been proposed subsequently: the criterion of behavioral equivalence (Morgan, 1977), a sensory modality being defined by the type of behavior generated by a specific stimulation, dedication (Keeley, 2002) which takes into account the evolutionary history of a species in order to determine to what sensory modality a putative sense organ has been evolutionary dedicated to, and the criterion of sensorimotor equivalence (O'Regan & Noë, 2001). A definition of a sensory modality can refer either to one of the mentioned criteria or to several of them in combination. Without detailing the advantages and disadvantages of each of these criteria (for a review, see Casati & Dokic, 1994), the aim of the following section is to discuss how each of these criteria can be applied to perception with SSDs.

3.1. Sensory organ and neurobiology

The first criterion for defining a sensory modality is the one of sensory organ, that is, which sensory organ is involved in perception (Grice, 1962). In a broader sense this criterion also takes into account how the sensory organ is connected to the brain (Keeley, 2002). For example, vision involves the eyes and associated visual brain areas; audition involves the outer ears, the cochlea, and associated auditory brain areas. We first consider the type of sensory organ and then the activation of the associated brain areas.

3.1.1. The type of sensory organ involved in perception

If a definition of a sensory modality is based on the criterion of sensory organ in a strict sense, that is referring to the specific sensory organ (the eyes for vision), then perception with a visual-to-tactile substitution device cannot be said to be visual. However, the criterion of sensory organ can be taken in a more lenient way and considered as fulfilled if there are enough relevant similarities between the visual system and the conversion system. Indeed, some relevant similarities exist between the visual system and visual-to-tactile SSDs (Morgan, 1977): (a) An image is formed on a bidimensional surface (the retina/the lens of the camera); (b) The surface that reacts to the incoming inputs contains discrete elements (rods and cones/vibrators); (c) These discrete elements are connected to neurons that send electric signals to the brain; (d) The device used to explore the environment (eye/camera) can be moved and such movements generate changes in the image; (e) In these two systems, the source of stimulation is not necessarily in contact with the body; (f) Perception can be interrupted by an obstacle between the observer and the perceived object.

Given these similarities, the differences between the visual system and SSDs seem to be mainly quantitative: SSDs have fewer receptors (i.e., the resolution in the image is low) and the possible movements of the camera are limited as compared with those allowed by the visual system. In addition, there are no colors. Are these structural differences sufficiently important to imply that perception with SSDs is not visual? First, it should be mentioned that such differences also exist among animal species. For example, the visual apparatus of the crab contains fewer receptor fields than those of most mammals, yet crabs are taken to see. Many other species, such as dogs, do not possess color vision. Thus, very different perceptual organs are classified as visual organs. Attempts to determine according to which specificities different visual apparatuses can be considered as sufficiently similar are highly problematic. If these criteria are too precise, we will obtain an inflation of the number of different sensory modalities which exist (Pacherie, 1997). On the other hand, if these criteria are broad enough to include, under the same term, the human visual system and the ones of the crab, dog, and bee, then, considering the number of similarities between the visual system and the perceptual prosthesis, there seems to be no reason to distinguish between the human and artificial ''organs.'' Moreover, technological innovations might bring future SSDs closer to human organs. As examples of such developments, we can refer to the ''retinal'' design of the PSVA (Capelle et al., 1998) and to the ongoing effort to code colors (Aiello, 1998). In summary, it cannot be denied that there necessarily remain many differences between a natural sense organ and an SSD. However, in the absence of any compelling theoretical reasons concerning which types of differences are relevant and which are not for defining a sensory organ as being visual, this leaves substantial room for maneuvering in the application of the criterion of a sensory organ.

3.1.2. Activation of the associated brain areas

In an extended sense, the criterion of sensory organ and neurobiology also involves the particular brain areas activated during the use of SSDs. Several studies have shown increased activation of the visual cortex while using visual-to-auditory substitution devices (De Volder et al., 1999; Renier et al., 2005a). Similarly, Ptito and his colleagues (Ptito & Kupers, 2005; Ptito, Moesgaard, Gjedde, & Kupers, 2005) showed increased activation of V1 after practice with a visual-to-tactile substitution device. Their study investigated changes in regional cerebral blood flow (rCBF) using positron-emission tomography (PET) in congenitally blind and normally sighted controls using the tongue display unit (TDU), a visual-to-tactile substitution device whose tactile matrix is displayed on their users' tongue. The participants had to learn to detect the orientation of visual stimuli presented through the TDU during a 1-week training period. The blind and sighted participants reached an equal level of performance after training. No task-evoked rCBF increase was detected in the visual cortex of either group before training. After practice, whereas tongue stimulation significantly led to an increase in CBF in the visual cortex of the blind participants, such activation was not found in the sighted controls. The authors concluded that, in the case of congenital blindness, training with a visual-to-tactile substitution device induces a rerouting of tactile information to the visual cortex that possibly involves strengthened or disinhibited parieto-occipital connections.

The increased activation of the visual cortex in trained blind users of an SSD might suggest that perception with an SSD becomes visual. However, this view involves the assumption that the same anatomical areas in the sighted and blind persons have the same function, that is, that the visual cortex necessarily sustains a visual function. According to an alternative, *functional* view, one brain area can sustain different functions (Hurley & Noë, 2003). Such interpretation is in line with recent research using transcranial magnetic stimulation (TMS) of blind and blindfolded sighted participants' visual cortex before and after TDU training. Before training, the participants in Kupers and colleagues' study (Kupers et al., 2006) did not report any subjective tactile sensation when TMS was applied over their visual cortex (only phosphenes were reported by sighted participants). After training, some of the blind participants (three out of eight early blind and one out of five late blind) reported somatopically organized tactile sensations that were referred to the tongue when TMS was applied over the occipital cortex, whereas no such sensations were reported by sighted participants. The authors concluded that the subjective character of the percept would depend on the stimulated sensory channel and not on the activated cortex. In other words, according to these authors, the subjective experience associated with an activity in the visual cortex after sensory remapping is tactile and not visual (see also Ptito et al., 2008).

The other important research area on crossmodal brain plasticity involves Braille reading. Indeed, brain imaging work using PET scans on congenitally and early blind participants revealed activation of the visual cortex during Braille reading, whereas blindfolded sighted controls did not show such activation (Sadato et al., 1996; Sadato et al., 1998; see also Buchel, 1998; Buchel, Price, Frackowiak, & Friston, 1998). The involvement of the visual cortex during Braille reading in blind persons was further evidenced by the results of a TMS study showing that functional blockade of the rewired cortex interferes with task performance (Cohen et al., 1997). In the study by Cohen and his colleagues, TMS applied to the visual cortex of early blind participants produced both errors in Braille reading and reports of tactile illusions (such as the feeling of missing dots or extra dots). Thus, in proficient Braille readers, the visual cortex can be recruited in order to perform a perceptual task with tactile stimulation and in addition, this gives rise to a tactile experience.

Overall, these studies reveal that the visual cortex can be activated by tactile stimulation in trained users of visual-to-tactile SSDs and Braille readers. In addition, studies using TMS suggest that, in blind persons, the function of the visual cortex and the qualitative expression accompanying its activation might be tactile. Does the latter result favor the dominance thesis, that is, the view that perception after practice with a visual-to-tactile SSD remains tactile? As suggested by Hurley and Noë (2003), the presence of tactile sensations does not imply that perception using a visual-to-tactile substitution device is exclusively tactile. These authors defend the view that the phenomenology associated with visual-to-tactile substitution devices cannot be exclusively tactile because the spatial content of this experience has the characteristics that are typical of visual experience. In particular, for users of a visual-to-tactile substitution device, the perceived objects are felt to be located at a distance from the perceiver, just as in vision, and unlike the case of tactile experience.

3.2. *Stimuli and properties*

The criterion of stimuli refers to the external physical stimulus types to which the specific senses are sensitive. According to this criterion, the senses are distinguished by reference to the physical specificities of their respective stimuli (Keeley, 2002). For example, vision is the detection of differences in electromagnetic stimuli and olfaction is the detection of differences in concentration of chemical stimuli. This criterion can be taken in two ways. First, it can be considered in relation to the stimuli that directly affect our bodies. In that case, perception with a visual-to-tactile substitution device cannot be considered as being visual because the physical stimulus is pressure rather than light. However, the criterion of stimuli can be construed as referring to the more distal source of stimulation. In that case, it refers to light in both visual perception and in perception with SSDs. Perception with visual-to-tactile and visual-to-auditory substitution devices thus fulfill the stimuli criterion because they provide access to the same distal source of stimulation, although it is obtained by different means than with unaided visual perception.

A related criterion is the one of the *properties* that are perceived (e.g., odors for smell, colors for vision). According to this criterion, a modality is considered as being visual if it leads to the perception of objects' visual properties such as their color or their brightness. This criterion is problematic if it is taken in isolation in order to characterize a sensory modality. Indeed, some of the objects' properties can be experienced by means of different sensory modalities. For example, shapes and textures can be sensed both by sight and by touch. This has led some authors to limit this criterion to a key property that would be accessible to only one sensory modality, for example, color for vision (e.g., Roxbee-Cox, 1970). However, this restriction does not solve all of the problems. It does not explain what is actually different in the perception of the same shape through vision or touch. In addition, this definition implies that we have a different sensory modality for each key property. We would thus have one tactile sense for perceiving the form of an object and other tactile senses for perceiving its properties of temperature, pressure, and texture (Casati & Dokic, 1994). Whatever the problems raised by the use of this criterion in order to define a sensory modality, SSDs can, at least theoretically, provide access to the same properties as those perceived by vision. That is, in the current state of technology, no device covers all visual properties, but technical progress can be made to include more properties (e.g., the implementation of a system for the extraction of colors in the TVSS; Aiello, 1998).

3.3. Behavior and function

Sensory modalities can also be distinguished by the type of behavior related to specific stimuli (Morgan, 1977). This criterion has been defined by Keeley (2002) rather narrowly as the ability to make discriminations between stimuli that differ only in terms of a particular physical energy type. This criterion can be broadened so as to include all types of behavior. Such a broader interpretation is in line with the doctrine of *functionalism* in the philosophy of mind (Putnam, 1960). According to functionalism, mental phenomena or mental states are defined by the role they play in mediating between inputs from the environment, other mental states, and behavioral outputs. In other words, if any neural, psychological, or mental state plays the same role as a visual state, then it is visual (for this line of functionalist reasoning in the context of sensory substitution, see Cole, 1990; Dennett, 1991; O'Regan & Noë, 2001). In particular, according to the behavior and function criterion if, confronted with a scene, users of SSDs show the same behavioral patterns (including mental behaviors such as thinking or imagining) as sighted people when confronted with the same scene, then they are considered to genuinely see.

Perception with SSDs seems indeed to give rise to comparable behaviors in response to light for sensorially impaired persons as vision for sighted persons. If the image projected on their skin expands, users of the TVSS will display similar avoidance behavior as sighted persons seeing a growing image (following expansion of the retinal image). Similarly, the vision of a dangerous animal for sighted persons and its conversion for users of SSDs will give rise to the same escape behavior. With respect to specific abilities allowed by the use of SSDs, the results obtained with the Voice (Auvray et al., 2007a) revealed that blindfolded sighted participants are able to use the auditory conversion of visual stimuli for locomotor guidance, object localization, and pointing. At first, participants had difficulties in obtaining precise depth information with the device but their performance improved with practice. Renier and his colleagues (Renier et al., 2005a) observed similar improvements with the PSVA. Interestingly, these authors reported that before training early blind participants had difficulties in localizing objects in depth, whereas blindfolded sighted participants seemed to apply the rules of visual depth from the beginning when they used the PSVA. However, after training, blind participants reached an equivalent performance level as that of sighted participants. With respect to object recognition, blindfolded sighted participants using the Voice can recognize three-dimensional objects and discriminate among objects belonging to the same category, such as two different plants (Auvray et al., 2007a). Pollok and his colleagues (Pollok et al., 2005) reported that participants' performance in the recognition of two-dimensional natural objects with the Voice improved with practice, even if the practice occurred with three-dimensional objects. In addition, studies with the PSVA showed that early blind individuals are able to recognize simple two-dimensional visual patterns thanks to their auditory conversion, with better performance than that of blindfolded sighted participants (Arno et al., 2001). These results reveal that blind persons can use SSDs in order to localize and recognize objects on the basis of light alone, although their performance might not reach the same level as that of sighted persons using vision. Thus, the extent to which the use of SSDs fulfills the behavior and function criterion becomes a matter of degree correlated with performance (i.e., the more perception with the device involves visual abilities, the more it resembles vision).

3.4. Dedication

Keeley (2002) has raised a criticism against a definition of sensory modalities based on the criteria of stimuli and behavior only. His line of argument is the following: Humans are easily capable of discriminating fully charged nine-volt batteries from dead ones simply by sticking them to the tongue. However, it does not follow from this that humans possess an electrical modality. According to Keeley, humans are capable of electrical *detection*, that is, they are able to discriminate electrical stimuli behaviorally. However, they are not capable of electrical *reception*: They do not carry out such discriminations in virtue of an anatomical system that has evolved because it allows discrimination of electrical stimuli. For Keeley, the evolutionary history of the putative sense to an organism has to be taken into account in a definition of sensory modalities. Thus, possessing a genuine sensory modality involves possessing an appropriately wired-up sense organ that has evolved in order to facilitate behavior with respect to an identifiable class of energy. As a consequence, we ought not to attribute an electrical modality to humans because electrical properties of the world are not part of the historically normal environment of humans' ancestors. Keeley's definition of a sensory modality thus includes the criteria of sensory organ and neurobiology, stimuli, behavior, and dedication, which are ''individually necessary and jointly sufficient.'' Following on from this definition, for Keeley, users of visual-to-tactile substitution devices are capable of visual detection but not of visual reception. The perceptual mode of interaction with the ''visual world'' remains tactile.

Even granting that Keeley successfully ruled out the possibility of having an electrical modality in humans, it can be questioned whether his argument implies that perception with the TVSS remains tactile. For, unlike in the case of electricity, the TVSS builds on an existing function in humans: seeing. Thus, the more perception with the TVSS confers visual abilities, the more it participates in an evolutionary established functionality, and the more it becomes ''dedicated'' itself. Keeley's argument about which function is considered as dedicated can be understood in terms of whether changes in the course of evolution were or would have been beneficial. Sensitivity to electricity could not have conferred advantages to humans due to the lack of electrical artifacts in the evolutionary past and thus it did not evolve as a dedicated function, but merely as a by-product of other functions. However, this is not true for the benefits of an SSD. If, miraculously, a functioning SSD had evolved, it would have been advantageous to blind ancestors even in the distant past, because having access to visual information is advantageous.

In summary, one can question whether the criterion of dedication really rules out categorizing perception with SSDs as being visual. Indeed, as the question is precisely whether perception with a visual-to-tactile or visual-to-auditory SSD can acquire visual functionality, applying the criterion of dedication begs the question. Besides this, one can also question the criterion directly, for it seems to be committed to ''historical chauvinism'' by privileging functions that have played a certain role in evolutionary history. This historical chauvinism rules out the possibility for any human-made bodily extension to acquire a genuine function.

3.5. Sensorimotor equivalence

The distinction between sensory modalities can also be made according to the criterion of sensorimotor equivalence. O'Regan and Noë (2001) explained the characteristics of each sensory modality in terms of the structure of sensory changes. What accounts for the differences between vision and audition, or any other sensory modality, is the structure of the laws sustaining the sensory changes produced by specific motor actions, that is, the sensorimotor invariants specific to visual exploration. For example, one of the laws that specify visual perception is the fact that when the eyes move, the image on the retina changes in a specific way. Also, when we blink, we interrupt the flow of sensory stimulation. A law differentiating vision from audition is that when we move forward to a source of stimulation, we obtain an expansion of the image on the retina in vision, whereas we obtain an increase in the sound intensity in audition.

According to the sensorimotor equivalence criterion, the nature of perception obtained with the use of an SSD becomes a matter of degree: The more perception obtained with an SSD shares sensorimotor invariants with visual perception, the more it resembles vision (Noë, 2004; O'Regan et al., 2005). In order to give an example, the use of a head-mounted camera shares more sensorimotor resemblance with vision than the use of a hand-held camera. Thus, a prediction made by sensorimotor theories of perception is that SSD perception with the use of a head-mounted camera will be considered closer to vision than when a hand-held camera is used instead.

The fact that it is necessary to actively manipulate an SSD before being able to perceive with it seems to confirm the important role of sensorimotor regularities in mastering visual abilities and in particular in developing visual-like *spatial* abilities. Such necessity of manipulative action has been illustrated by the pioneering work of Bach-y-Rita and his colleagues (Bach-y-Rita et al., 1969). In this study, the camera of a visual-to-tactile substitution device was at first fixed. Under these conditions, users of the device acquired only very limited abilities for discrimination of the received stimuli. Once users were given the possibility to hold the camera and to perform several movements with it, they then became able to perceive with the device. A plausible explanation is that, when actively manipulating the camera, users can establish the links between their actions with the device and the resulting changes in sensory stimulation, and that tracking these links is a precondition for successful perception.

The necessity of action in order to perceive with SSDs reveals that the access to visual information by means of tactile inputs is not immediate. Perceiving by means of these devices does not correspond to a passive transfer of information from one sensory modality to another: It requires perceptual-motor learning. Thus, users' movements seem crucial for learning to properly perceive with a sensory substitution device. A parallel can be drawn with natural vision: If the eyes are prevented from moving, perception is impaired (Ditchburn, 1973; Noë, 2004; Steinman & Levinson, 1990; see also Held & Hein, 1963, for the effect of the restriction of kittens' bodily movements on perception). Visual perception and perception with an SSD are thus possible only when actions structure perception.

In addition, action seems necessary not only to recognize objects but also to perceive them as located in three-dimensional space. Indeed, studies have shown that, after training, the succession of proximal stimulations generated by the use of SSDs can be attributed to exterior and distant causes. For instance, after training with the TVSS, users no longer have the experience of a tactile image on their skin, but they directly attribute the cause of the stimulations to a distant object (Bach-y-Rita, 1972; White, Saunders, Scadden, Bach-y-Rita, & Collins, 1970). Users' verbal reports leave no doubt that the proximal stimulations (as well as the possible skin irritations) produced by the tactile matrix are clearly distinguished from the distal perception. This distinction between proximal stimulation and distal perception is also revealed by the fact that once users are trained, the location of the camera and the location of the tactile stimulators are no longer important. The camera can be moved from the hand to a head-mounted display and the tactile stimulators can be moved from the back to the abdomen without loss of performance. An explanation for this is that trained users no longer feel the images on their skin but they acquire a direct perception of distal objects (Bach-y-Rita & Kercel, 2003). Bach-y-Rita (2002) reported the following anecdote: One of the participants in his study was wearing the tactile matrix on his back. Then, without the participant knowing, the supervising scientist caused the camera to zoom, which provoked a rapid expansion of the tactile image on the participant's back. The participant had a rapid backward movement, as if an object was arriving in front of her. Similar observations have been made with visual-to-auditory substitution devices. For instance, one user of the Voice (Meijer, 1992) related that at the beginning she just heard sounds without attributing any meaning to them (as proximal stimulation). However, after training, she was able to distinguish sounds made by the device from other sounds, and via these sounds she perceived objects as located in a three-dimensional space, thus distally (Fletcher, 2002). The use of quite a variety of tools shows comparable results of exteriorization. For example, a blind person using a cane experiences the stimulation at the end of the cane rather than in the hand, where the tactile stimuli are received (Bach-y-Rita, 2002). Similarly, the haptic experience of the contact with a tool, which is at first proximal can, after training, be projected to the end of the tool (e.g., Holmes, Calvert, & Spence, 2004; Holmes & Spence, 2006; Maravita, Spence, Kennett, & Driver, 2002).

Hurley and Noë (2003) have argued that, due to the importance of the sensorimotor equivalences between natural and TVSS perception, perception with the TVSS belongs primarily to the substituted modality. In particular, their defense of the thesis that perception with the TVSS is similar to genuine seeing emphasizes sensorimotor equivalence. For these authors ''What it is like to see is similar to what it is like to perceive with TVSS because seeing and TVSS-perception are similar *ways of exploring the environment*: they are governed by similar sensorimotor constraints, draw on similar sensorimotor skills, and are directed toward similar visual properties, including perspectivally available occlusion properties such as apparent size and shape. These similarities go beyond just providing spatial information; they extend to the distinctively visual way in which dynamic sensorimotor interactions with the environment provide information to the TVSS-perceiver'' (Hurley & Noë, 2003, pp. 144–145).

3.6. Qualitative experience

A final criterion used to distinguish between the senses is the one of qualitative experience. In its standard interpretation, the criterion of qualitative experience refers to what is now often discussed under the term of ''qualia'' or ''phenomenal feel.'' A sensory modality would then be characterized by a specific (e.g., visual or auditory) feeling attached to it. In the context of sensory substitution, the criterion of qualitative experience has also acquired a nonstandard interpretation, namely as referring to emotions associated to perceptions (e.g., Bach-y-Rita, 2002).

The term ''qualia'' refers to the subjective properties of experience or how a certain physical stimulus is experienced consciously. Qualia are often defined as nonobjective and internal properties that in perception appear somewhere between the reception of the stimulus and the ensuing behavior (Churchland, 1988). The felt character or ''what it is like'' (Nagel, 1974) to perceive with a perceptual prosthesis can be approached by means of users' verbal report. In the study by Auvray and her colleagues (Auvray et al., 2007a) blindfolded sighted participants were trained with the visual-to-auditory substitution device the Voice for 15 hr. The participants in this study were given questionnaires about their qualitative experience while using the device. The participants were asked which sensory modality their experience most resembled for localization tasks and for recognition tasks. Localization tasks were more likely to be apprehended either as giving rise to visual experiences or, interestingly, as belonging to a new sense. Recognition tasks were judged as more closely resembling audition. Two participants mentioned a resemblance with the tactile modality. In addition, an important finding was that the participants often emphasized that they simply had the feeling of mastering a new tool. They felt that they could easily acquire mastery of it because, as one participant said: ''We are used to extending our bodies through machines, exactly as when we learn how to drive a car or how to use a computer.'' Thus, in this study, while the participants were able to perceive visual properties when they are converted into sound, they did not strictly speaking have a visual phenomenal experience or an auditory one. Indeed, the reported qualitative experience was not necessarily assimilated to either the substituting or the substituted modality; rather, the participants' phenomenal experience was task dependent and its tool-like nature was emphasized.

With regard to the emotional aspect of the qualitative experience criterion, it seems that perception with SSDs lacks associated emotions. In spite of all the possibilities offered by these devices, they do not lead to the emotional responses one would expect in the case of unaided perception. Two examples reappear in the literature: A person blind from birth was shown an image of his wife, and two blind students were shown pictures of nude women. Although they were able to describe the details of the image, they reported that there was no emotional content associated to their perception (Bach-y-Rita, 2002). Thus, what seem to be missing in this mode of perception are the emotions associated to the perceived objects.

The use of SSDs thus seems to show that an isolated user cannot spontaneously experience the values and emotions normally conveyed by a perceptual experience. The shapes perceived in one sensory modality are not directly associated to the sensations of pleasure and pain felt during the perception of a similar form in another sensory modality. However, it does not seem surprising that the appropriate emotions are not immediately and spontaneously felt. Expecting they would be would involve the idea that emotional significations are intrinsic to things and that we just need to access them during a perceptual process, as if it was a matter of registration of information. However, emotions are not intrinsic to objects themselves but rather arise from the various ways perception of each object leads us to act (e.g., Lenay, 2002). The hypothesis that the absence of felt emotions is not due to the involvement of a perceptual prosthesis itself is supported by the existence of similar reports of absence of emotions and meanings felt by patients whose vision has been restored after having been born blind with congenital cataract. Patients recovering sight by a removal of cataract report that there are no affective qualities associated with colors and that seeing faces is not associated with any emotional content (Gregory, 1966, 2003).

Two hypotheses, not mutually exclusive, can be put forward to give an account of the lack of emotions experienced while using a perceptual prosthesis: The hypothesis that the feeling of emotions requires a perceptual learning process and the hypothesis that emotions can only arise by the intersubjective building of values in a community of persons with similar means of perception. The first hypothesis suggests that emotions could be developed with a longer or earlier use of the device. Using an SSD from childhood might allow the information accessed through the device to acquire an affective content. Attempts of equipping babies with TVSS suggested positive results (e.g., the babies smile when perceiving their mother; Bach-y-Rita et al., 2003).

According to the second hypothesis, the existence of a community of users might stimulate the constitution of common values associated with the perceived objects. In that case, the intersubjective use of a perceptual prosthesis would allow both the acceptance of an unusual apparatus and the establishment of values associated with the world perceived by the prosthesis. It should be noted that observations on the purely individual use of SSDs are mainly reported in the literature. The user is surrounded by persons that do not rely on the same means of perception. The user consequently might easily feel that he is wearing a ridiculous apparatus. However, there is no such thing as a grotesque apparatus per se: Weirdness only arises from the isolated character of a particular form. Each new technology that acquires social recognition establishes new traditions. The prosthesis, once becoming common and socially accepted, disappears in favor of the perceptual world it opens up to the community of users. More important, the user of a perceptual prosthesis, beyond being unique in being outfitted with odd-looking equipment, is isolated in a perceptual mode that he cannot share. It seems a plausible hypothesis that perceptual values are linked to a shared history, arising from interactions of several persons in a common environment defined by the same means of access to it (Auvray, Lenay, & Stewart, 2009; Lenay et al., 2003).

4. Discussion

4.1. Dominance or deference?

What should be concluded from this review of criteria concerning which sensory modality perception with an SSD belongs to? Do the criteria favor the dominance thesis according to which perception with a visual-to-tactile or visual-to-auditory substitution device remains in the substituting modality (touch or audition)? Or, alternatively, do the criteria indicate that perception changes for the substituted modality (vision), thereby confirming the deference thesis?

The case for dominance made by Humphrey (1992), Block (2003), and Prinz (2006) is based on the traditional distinction between sensation and perception with an emphasis on the felt sensations. According to these authors, given that TVSS users keep on feeling tactile sensations, their perception with such a device remains in the substituting modality. Thus, their case for the dominance thesis relies on the criterion of qualitative experience. The sensationalist line of defence for dominance developed by these authors can be criticized for overemphasizing the role of sensations in perception. As pointed out by many theorists and particularly eloquently by Hanson (1958), in seeing an object such as a house, we do not have two consecutive visual experiences, one of colored dots and a subsequent one of a house. Instead, we immediately experience the perceived house. Hanson (1958) points out that, although one can, by attentional processes, become aware of simpler sensation-like constituents of perceptions, this ''sensational'' way of perceiving is a distinct and very specific way of perceiving. Similarly, according to Noë (2004), despite the fact that, by adopting a specific stance, one can become aware of experiences in terms of sensations, perceptions themselves cannot be reduced to a simple aggregation of their constituting sensations. He refers to the use of a cane as revealing that the sensations recede to the background while experience acquires its own distinct characteristics.

Interestingly, the defence of the dominance thesis offered by Keeley (2002) rejects the criterion of qualitative experience as a valid determinant of what is a sensory modality. Keeley arrives at dominance through another route, namely via a strong emphasis on the criterion of dedication. According to Keeley, experience with the TVSS remains tactile because the TVSS is not evolutionarily dedicated to seeing. In the previous section, we have indicated the extent to which Keeley's line of argument is problematic.

The deference thesis has been defended by Hurley and Noë (2003). According to them, the substituting modality is ''overruled'' by the substituted modality and TVSS users acquire visual experience. Several of the criteria discussed in the previous sections can be used in favor of this view. In particular, perception with SSDs involves sensorimotor equivalences, a similar functional/behavioral potential, and direction toward similar visual properties. The deference thesis developed by Hurley and Noë relies strongly on the criterion of sensorimotor equivalence and especially on the fact that the spatial properties perceived with the TVSS share more resemblance with visual spatial properties than with tactile spatial properties (see also Auvray, Philipona, O'Regan, & Spence, 2007b). Noë (2004) has further elaborated this position by adding important nuances with respect to the level at which sensorimotor equivalences can be obtained. He concedes that, at the finer levels, there are many sensorimotor differences between natural vision and perception with a SSD. However, the same does not apply for equivalences at a higher level (for instance, the level at which a description in terms of occlusion becomes relevant). According to Noë, the existence of high-level equivalences between unaided vision and perception with SSDs allows the latter to be categorized as visual. It should be noted that Noë's account of SSD perception remains, however, underdeveloped as he does not specify in detail neither which equivalences count as high-level nor why high-level equivalences are more important than low-level ones for defining a sensory modality.

In summary, the defence of dominance is strongly dependent upon either the criterion of dedication or the criterion of qualitative experience applied to sensations, both of which can be criticized, as we have indicated. On the other hand, the deference thesis finds support in the criteria of stimuli and properties, behavior and function, and sensorimotor equivalences. However, as will be detailed below, perception with an SSD goes beyond assimilation to either the substituting or the substituted modality.

4.2. *Beyond dominance and deference: Sensory substitution as perceptual extension*

In this final section, we propose an interpretation of perception with SSDs that not only goes beyond dominance but beyond deference as well: an interpretation based on the idea of an addition, augmentation, or extension of our perceptual abilities. Under this view, SSDs should be seen as tools that extend perception in entirely novel ways. This dimension of novelty has been absent or insufficiently developed in the existing interpretations of SSDs. Both defenders of the dominance and deference theses have tried to assimilate perception with SSDs to perception in an existing sensory modality. But might perception with SSDs not lead to a new form of perceiving and experiencing?

Our proposal is that SSDs belong to the category of what have been called ''mind-enhancing tools'' (METs; Clark, 2003) such as sketchpads or computers. Recent analyses have brought to the fore that such devices should not be understood, as used to be the case, as merely external stand-ins for already existing purely internal processes (Clark, 2003; Menary, 2006, 2007). Rather, METs provide means of expanding cognition in ways that would have been impossible without them. Under this view, METs and the cognition provided by them cannot be reduced to something already available before their use. The same, we contend, applies to SSDs: They provide novel forms of interaction with the environment that cannot be reduced to perception in one of the natural senses. It follows from this view that the assumption underlying the debate on dominance versus deference no longer holds, since, in our proposal, perception with SSDs occurs neither in the substituting nor in the substituted modality.

Let us start with having a closer look at METs and the way they can be interpreted. What is uncontroversial about METs such as pen and paper, sketchpads, and computers, is that, in processes such as the production of a written text, a drawing, or a calculation, they allow the storage of certain results. According to a first interpretation, the role of METs is mainly to reduce the workload of internal resources. METs, then, only make it easier to perform in an externally supported way cognitive operations that are normally performed exclusively by relying on unenhanced resources (memory being foremost among these). METs would then contribute to cognition in a quantitative rather than in a qualitative fashion. They would support cognitive functioning, not by making novel operations possible, but by facilitating the already available cognitive operations. This interpretation of METs flows from a conception of cognition according to which everything properly called ''mental'' and by extension ''cognitive'' is internal to the brain or to the body. According to this view, the use of external tools cannot genuinely transform cognition; in other words, the causal coupling of a tool and its user never constitutes a new form of cognition.

A second interpretation of METs has been proposed according to which METs do transform cognition in a qualitative way (Clark, 2003; Menary, 2006, 2007). Novel tools not only facilitate established cognitive processes; they can also allow for the appearance of novel cognitive operations, which simply would have been impossible without them. For example, without the proper means and tools to write down, calculate, or draw diagrams, human cognitive abilities would not have evolved to their current state. An interesting illustration of this view is provided by Clark (2003) who referred to the work done by van Leeuwen, Verstijnen, and Hekkert (1999) on the role of sketchpads in the production of certain forms of abstract art. Van Leeuwen and his colleagues showed that the creation of multiply interpretable elements in drawing, typical in much of abstract art, is essentially dependent on the use of external sketches. They claimed that this is due to the difficulty of holding several and simultaneous interpretations of images in the mind. It is only by externalizing an image that its many possible interpretations can be generated and combined in a reliable enough way to guide a design process. Thus, the use of a sketchpad genuinely opens up possibilities for new forms of artistic creation that would not have existed without them (Clark, 2003). What emerges then is a form of extended cognition in which established elements and operations are closely integrated with additional ones in order to form a single novel ''unit of cognitive analysis'' (Menary, 2006).[1]

As Clark (2003) points out, the role of tools in cognition shows that the concept of cognition ought to be reconsidered in the light of the criteria of fluid integration and transformative potential. A tool that we learn to use in a fluid manner becomes transparent. ''Transparent'' here refers to the fact that, after training with a new tool, users subsequently feel immersed in the task allowed by the tool, rather than being aware of manipulating the tool itself. The more transparent a tool becomes, the more it augments fluidly its user's cognitive potential. For instance, when the cane becomes transparent, the tactile sensations recede to the background for its experienced user. We defend the view that this second interpretation of METs applies to SSDs. These systems should also be understood as transforming sensorimotor and perceptual capacities, rather than being reduced to the exercise of one of the natural senses, either in the substituting or in the substituted modality. Under this proposal, SSDs are complementary and compensatory. They do not completely substitute for the loss of a natural sense; rather they complement an existing sense (the substituting modality) so that it extends to acquire a novel functionality that partly compensates for the lost sense (the substituted modality).[2] SSDs can become integrated to such a degree that one can speak of a novel form of perceptual/sensorimotor interaction (Lenay et al., 2003). Under this interpretation, the initially artificial and tool-like nature of SSDs is emphasized but, as in the second interpretation of METs, due to their potential for fluid integration and transformation, they are considered as constituting a novel form of perception.

As with other types of METs, the fluid integration of SSDs requires a learning process (Auvray et al., 2007a). At the very beginning of this process, experience is restricted to proximal stimulation in the substituting modality. At the next stage, people use explicit reasoning for deducing the distal layout from the proximal sensations. At the final stage, experience is more directly focused on the distal stimulus so that users directly have access to the perceived object without the need of explicit inferential processes. Thus, after training, the device the Voice becomes transparent and users forget about the auditory stimulation it delivers. However, under other circumstances (mainly those where routine tool use no longer suffices) users have to concentrate on how to use the tool in order to master a difficult task. In this case, the tool itself and the sensations that directly flow from its manipulation become fully conscious again and then perception seems to belong to the substituting modality.

The fact that the use of an SSD leads in its final stage to direct recognition of the distally stimulating object does not imply that the learning process should be considered as being entirely similar to the development of natural perception. Indeed, the learning process during which users become skilled in using an SSD is in several aspects unlike the development of natural sense experience. Not only is there a difference between becoming skilled in using an SSD through a learning process requiring conscious effort, there also remain important differences in the final or mature stages. There is no analog in natural perception to the way the user of an SSD retains explicit and conscious control over it even after having become skilled. We do not have conscious control over precise details of eye movements in the way the users of SSDs have control over their movements with the device (see Hutto, 2005). On the other hand, technological developments and use starting at early infant age might lead to a level of integration of SSDs with their users' body such that its artificiality might become irrelevant (Clark, 2003). It should be emphasized that, from an evolutionary point of view, the regular sense organs have been add-ons themselves. For every sense organ, and every organism perceiving by means of it, there is a time in evolutionary history in which the sense organ was absent in the predecessors of that organism. Yet the integration of those evolving sense organs in the organism which is dealing with the environment, no matter how gradually it happened, has led to the establishment of a sensory modality of its own. There seems to be no good reason, on pain of becoming a ''historical chauvinist,'' to restrict this possibility to organs that have arisen through natural evolution. Thus, just like our sense organs, seen as ''organic tools,'' have led to our natural sensory modalities, SSDs might give rise to what could be called a novel sensory modality (subject to a sufficient degree of integration of SSDs to their users' bodily functioning, which might not be technically possible yet).

In summary, previous debates on the nature of perception with SSDs have been driven by the assumption that it should be assimilated to perception in one of the existing senses: either the substituting or the substituted modality. Opposite to this view, we have emphasized the tool-like nature of SSDs and in particular its similarities with other types of METs, which expand their users' perceptual abilities in novel directions. Following on from the proposed interpretation of SSDs, both sides of the debate on dominance versus deference can be criticized for having failed to fully appreciate that SSDs provide a new form of perceptual coupling with the environment (see also Lenay et al., 2003). By reducing experience with SSDs to one of the existing modalities, both theses deny their transformative potential, or at least its full extent. By emphasizing that experience remains wedded to the substituting modality, attackers of the dominance thesis have overlooked transparency. As discussed above, defenders of the deference thesis (e.g., Noë, 2004) have criticized the sensation-based defences of the dominance thesis precisely for underestimating the ways in which perceptual experience departs from its sensory underpinnings. Our proposal takes this conception of perception as being flexible one step further. We contend that perception can not only transcend its sensory origins, but it can move beyond the confines of the traditional senses.

Notes

1. An early proponent of such an approach was Morgan (1977). According to him, if blind persons are provided with the same information using SSDs as sighted persons through vision and if they respond to this information in a similar way, then we do not have any alternative but to say that they see. Thus, according to Morgan, there is no reason to think that if two sensory inputs provide access to the same information and give rise to the same behavior, persons will perceive differently, even if the information comes from different pathways. Functionalism in the philosophy of mind also usually includes, besides behavior, a reference to the stimulus type (Churchland, 1988). Thus, among the views that aim to characterize a sensory modality by reference to the stimulus criterion, a distinction has to be made between the ''stimulus view'' (which involves only a reference to the type of stimuli used in perception) and the ''stimulus plus function view'' (which involves in addition the behaviors induced by specific types of stimuli, i.e., the behavior criterion).
2. In this way the functioning of SSDs is different from one of the more mundane devices such as glasses or telescopes. Glasses and telescopes operate within the confines of the visual sensory modality by changing the spatial relationships between the observer and the perceived object (e.g., by bringing a distant object visually closer in

the case of telescopes). On the other hand, SSDs combine several sensory modalities; these devices build on the substituting modality (touch) with the aim not to restore that sensory modality but rather to obtain a functionality comparable to the one which normally belongs to another sensory modality: the substituted modality (vision).

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