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The perception of space and form recognition in a simulated environment: The case of minimalist sensory-substitution devices

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Abstract. Whenever we explore a simulated environment, the sensorimotor interactions that underlie our perception of space may be modified. We investigated the conditions under which it is possible to acquire the mastery of new sensorimotor laws and thereby to infer new perceptual spaces. A computer interface, based on the principles of minimalist sensory-substitution devices, was designed to enable different possible links between a user's actions (manipulation of a mouse and/or keys of a keyboard) and the resulting pattern of sensory stimulation (visual or auditory) to be established. The interface generated an all-or-none stimulus whose activation varied as a function of the participant's exploration of a hidden form. In this study we addressed the following questions: What are the conditions necessary for participants to understand their actions as constituting a displacement in a simulated space? What are the conditions required for participants to conceive of sensations as originating from the encounter with an object situated in this space? Finally, what are the conditions required for participants to recognise forms within this space? The results of the two experiments reported here show that, under certain conditions, participants can interpret the new sensorimotor laws as movements in a new perceptual space and can recognise simple geometric forms, and that this occurs no matter whether the sensory stimulation is presented in the visual or auditory modality.

1 Introduction

Technical devices transform our ability to act and to perceive. Tools, perceptual prostheses (eg glasses, binoculars, sensory-substitution systems), and computer-based interfaces (virtual-reality, telepresence) enlarge our capacity to act and to feel. Such devices allow their users to engage with different sensorimotor spaces and, as such, they open up an experimental field of research into the epistemology of perception. The issue of the mastery of a new sensorimotor space is, in the first instance, a theoretical one, because it may confirm or refute the predictions made by different theories of perception. The issue is also, however, a pragmatic one since the conception of technical devices should benefit from any advance in our understanding of the conditions necessary for their mastery.

1.1 *Sensory-substitution devices and the constitution of new sensorimotor spaces*

Of particular interest here is the case of so-called 'sensory-substitution' devices. These devices provide, through a given sensory modality (for example, touch), the kind of information that is usually provided by another sensory modality (for example, vision). One of the first such systems, the Tactile Vision Substitution System (TVSS), converted an image detected by a video camera into vibratory stimulation applied on the user's back (Bach-y-Rita et al 1969). Several other devices have been developed subsequently, based on various kinds of information and sensory stimulation (eg Bach-y-Rita 1998; Capelle et al 1998; Cronly-Dillon et al 1999; Kay 1964; Meijer 1992). Research has shown that people can make use of such tools, provided they have active control over them

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(Auvray et al 2005, 2007; Bach-y-Rita 2002; Lenay et al 2003). Such results demonstrate the structural and functional plasticity of our sensory systems, and have raised hopes with regard to the development of non-invasive apparati to help individuals with sensory impairment. These results have also been used as an argument for a radical sensorimotor account of perceptual experience (Lenay 2002; Noë 2005; O'Regan and Noë 2001; Stewart 1995).

Among the most important issues investigated by researchers working with sensory-substitution devices thus far are the questions whether users will come to report subjectively that they feel as though they are faced with a sensorimotor coupling of a spatial nature and, if so, whether they will exhibit spatial-like abilities, as measured by their objective performance. There are two main reasons to focus on such spatial issues: first, tool use provides a particularly interesting means of studying the reorganisation of perceptual space. For example, haptic experience of the contact with a tool, which is at first proximal, can, after training, be projected to the end of the tool (eg Holmes and Spence 2006). More specifically, with regard to sensory-substitution devices themselves, visual-to-tactile conversion systems favour a focus on the contrast between the distal character of visual perception on the one hand (objects are visually perceived as being 'out there' in the world, not as the stimulation of receptors on the back of our eyes), and the proximal character of tactile perception (as experienced prior to any training with a tool) on the other. As a result, when 'visual' information is provided via the tactile modality, distal attribution naturally emerges as a genuine criterion necessary for assessing the mastery of the device at the level of the information provided rather than at the level of the sensory modality used (eg Bach-y-Rita 2002; Lenay et al 2003).

The second reason to focus on spatial issues is that, among all aspects of perception, the perception of space is the most likely one to arise from the mastery of sensorimotor interactions, as compared, for instance, with the perception of colour. Indeed, at least since the time of Poincaré (1905, 1907) and Helmholtz (1909), then later Piaget (1936, 1937), the idea that space is not defined at the level of mere sensory stimulation, but rather at the level of our sensorimotor interactions has been clearly elucidated. For instance, Helmholtz pointed to the following idea: actions that can cancel each other out from the viewpoint of sensory inputs determine a (mathematical) group structure, and properties of such a group characterise displacements within a geometrical space. Therefore, on general grounds, one might expect that the mastery of a sensory-substitution device would work primarily at the level of the constitution of a new space, and consequently we first decided to investigate this point.

1.2 *The example of minimalist devices*

Minimalist sensory-substitution devices illustrate particularly clearly how the constitution and mastery of a new space is grounded on the basis of the sensorimotor laws linking users' actions with resulting patterns of sensory stimulation. These devices provide very little sensory information, possibly as little as one bit (ie all-or-none stimulation). Indeed, in such cases, individual stimuli carry no cues by themselves concerning space and therefore users cannot infer space on the basis of an analysis of the sensory stimulation alone.

The Suppléance Perceptive Team at Compiègne has developed a sensorimotor coupling that has been deliberately reduced to the bare minimum (see Lenay 2002). This device consists of a single photoelectric cell, fixed on the forefinger of one hand and connected to a single vibrotactile stimulator attached to the other hand. The activation of the vibrotactile stimulator occurs whenever the light intensity exceeds a certain threshold (see figure 1). This device has only one point of stimulation corresponding to a unique 'receptive field'. The sensory stimulation obtained from this device is thus reduced to a sequence of discrete all-or-none stimulations which, by themselves, cannot convey a spatial interpretation.

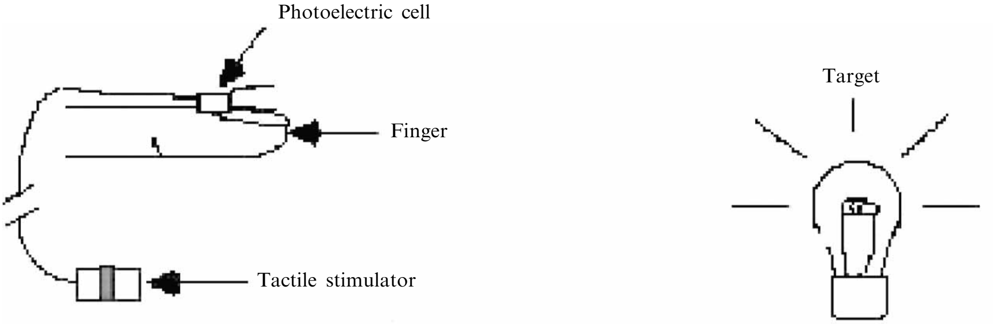


Figure 1. Schematic illustration of Lenay's (2002) sensory-substitution device (Suppléance Perceptive Team at Compiègne).

Nevertheless, blindfolded participants who use the device rapidly develop spatial localisation and distal attribution abilities for the stimuli accessed through the device. By means of their control of the position of the photoelectric cell, the temporal succession of sensations they receive often seems to them to be linked to a single distal object, and the proximal vibrations caused by the tactile stimulator are clearly distinguished from the distal perception itself. After several minutes of exploration with such a device, participants are typically able to indicate the direction and approximate distance of the luminous target (Hardy et al 2000). It is important to stress that, when the participants do not move, the stimulation is experienced as being located on the skin and exteriorisation of the position of the target never occurs. It is also interesting to note that the exact nature or the position of the stimulus on the body has no bearing on people's perception of the distal stimulus. The stimulus can consist of an auditory beep or a vibration applied anywhere on the body; it has no effect on participants' performance (Lenay 2002). Results such as these have led to the view that, in this framework, what is important is not the nature of the sensory input itself, but rather the sensorimotor invariant structure of the changes in sensation.

Thus, minimalist devices represent limited cases for which the constitution of a new space and distal attribution can emerge from nothing more than sensorimotor interactions. However, in such cases, participants' motor commands are already constituted as movements in space. In order to show that the constitution of a new perceptual space is possible only by an extraction of sensorimotor invariants linking a participant's actions to a resulting pattern of sensory stimulation one has to modify one's motor commands in such a way that they cannot immediately be understood in terms of a particular spatial displacement.

1.3 *Sensory substitution and distal attribution*

The results obtained with visual-to-tactile sensory-substitution devices (eg Bach-y-Rita 2002) and minimalist devices (eg Hardy et al 2000) have revealed that participants are able to attribute their sensations to a distal and exterior cause. However, in these earlier experiments, the participants had prior knowledge of the functioning of the device; they therefore knew that a distant object would be the cause of their sensations. The question therefore arises whether distal attribution would occur if participants did not have any prior knowledge of the link between their actions and the resulting sensory stimulation.

In order to approach this question, Epstein and his colleagues (1986) equipped the participants in their study with a visual-to-tactile substitution system without telling them of this fact. Participants then manipulated a lever with an object fixed on top.

The sensory-substitution device converted the form and position of the object into a pattern of tactile stimulation which the participants felt on their skin. At the end of a period of exploration, the researchers investigated the extent to which distal attribution had occurred via the rating of possible explanations of the participants' experience with the device. The results of Epstein et al's study showed that the participants were able to correctly understand that there was a link between their actions and the resulting pattern of sensory stimulation. However, they never developed the hypothesis of distal attribution. That is, they never understood that the cause of their sensory experience was due to an encounter with an object perceived via the device.

These results show that distal attribution does not necessarily occur in the absence of prior knowledge of the functioning of the device. However, the manipulation of the lever used in Epstein et al's study, owing to the large number of degrees of freedom it involves, may have prevented the participants from achieving a sense of distal attribution. In addition, the stimulation that was provided by the sensory-substitution device consisted of several simultaneous tactile stimuli that spatially corresponded to the converted visual form (analog conversion). Thus, the tactile sensory stimulation provided to the participants was already spatially organised.

In order to study the conditions that are necessary for distal attribution to occur, it is necessary that: (i) users of a novel device do not know that the sensory stimulation they receive can be attributed to the exploration of an external object; (ii) the space of displacement allowed by the device is different from our previously acquired space of displacement [in contrast with Hardy et al's (2000) experiment]; (iii) the sensory stimulation provided to the participants does not contain, per se, any spatial information [contrary to Epstein et al's (1986) experiment].

1.4 *Aim of the present study*

The aim of the present study was therefore to investigate if the constitution of a new sensorimotor space is based on sensorimotor interactions and does not need to rely on a previously acquired representation of space. To address this question a displacement space was established that was different from our physical space, and a pattern of sensory feedback was developed that did not in itself contain any spatial information. To this end, a simple computer interface was used to establish various different links between a user's actions and the resulting pattern of sensory stimulation. The sensory stimulation varied as a function of the exploration of a hidden form within the simulated space. Two alternative patterns of sensory stimulation and two alternative forms of action were used.

The sensory feedback that participants received could be constituted either by a visual signal (a black or white square appearing at a fixed position on a screen) or by an auditory signal (a high-pitched or low-pitched sound). These two conditions were used to investigate what influence, if any, the sensory modality in which the feedback was presented would have on participants' performance. In the framework of sensorimotor theories of perception, the constitution of a new perceptual space should not rely on the nature of the sensory stimulation itself, but rather on the sensorimotor invariant structure of the changes in sensation (eg O'Regan and Noë 2001). We thus predicted that participants' performance should not be affected by whether the all-or-none sensory feedback was provided in the visual or auditory modality.

Participants' actions could be constituted by movements of a mouse and/or by a sequence of key-presses on a keyboard. While the first alternative engages participants in a sensorimotor interaction involving continuous proprioceptive information concerning their location within the simulated space, the second alternative leaves participants with sequences of essentially all-or-none sensory inputs, both at the exteroceptive and at the proprioceptive levels. These two conditions were used to investigate whether participants actually 'discover' a new space or merely rely on a subset of their prior practical knowledge of space based on proprioceptive information. It should be noted that the interfaces involved, that is the mouse and the keyboard, were by no means new to our participants. However, the links between their actions with these devices and the resulting all-or-none sensory feedbacks were unusual to our participants and, as such, they constituted a new sensorimotor environment.

In experiment 1 we investigated the cognitive reaction of participants to the sensorimotor interface they used. The aim of this experiment was to investigate the conditions that are necessary for participants to understand their actions as constituting a displacement in a simulated space without being told anything about the apparatus beforehand. In a second experiment, to determine whether distal attribution was correlated with the accuracy of exploration allowed by the manipulation of the device, we investigated participants' abilities to recognise simple forms within the sensorimotor spaces accessed through the interface, when tested against different conditions of possible actions and sensory stimulation.

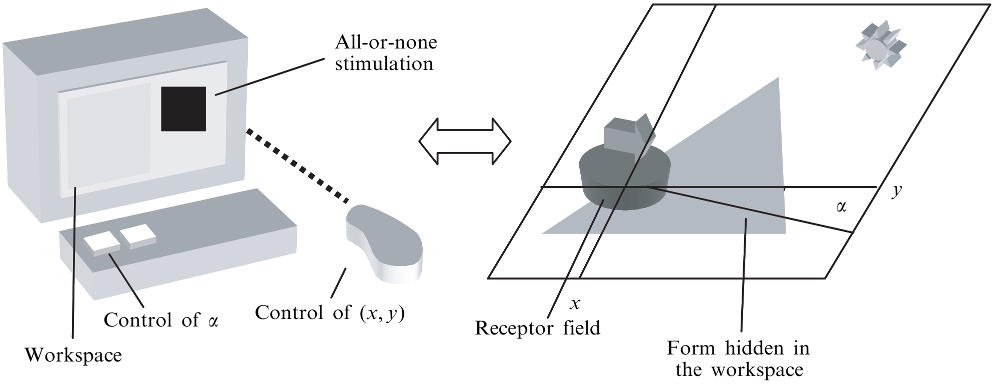
2 Experiment 1: Genesis of the perception of space in a simulated environment

In experiment 1 we investigated the genesis of the perception of space when people interact with a new sensorimotor environment. The participants in our study were given a device whose use was new to them, without its functioning being explained. We searched for the minimal conditions that were necessary for participants to understand that their actions resulted in the displacement of a virtual sensor (avatar) in a simulated space, and to understand that the variations in the sensory stimulation that they received corresponded to modifications in the position of the virtual sensor in relation to an object situated in this space.

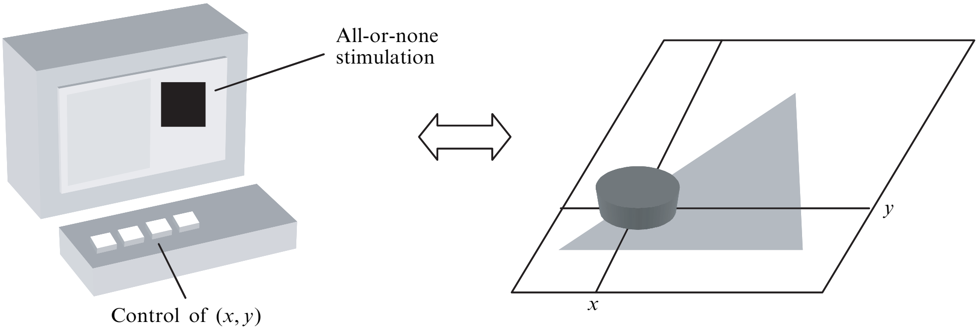
2.1 *Methods*

2.1.1 *Apparatus.* The participants' actions determined the displacement of an invisible circular, 0.2 cm in diameter, virtual sensor within a 9 cm × 9 cm grey workspace. The position and orientation of the virtual sensor could be changed by manipulation of a mouse and/or by pressing the keys on a computer keyboard. A 4 cm × 4 cm square target was placed close to the middle of the workspace. This target form was invisible to the participants, but gave rise to an all-or-none pattern of either auditory or visual sensory feedback whenever one or more of the pixels of the virtual sensor overlapped it. The auditory feedback consisted of a higher-frequency tone (466 Hz) when the virtual sensor was on the form and a lower-frequency tone (82 Hz) when it was not. The visual feedback consisted of the presentation of a 3 cm × 3 cm white square displayed on the middle right of a computer screen when the virtual sensor was on the form and a black square when it was not. At the beginning of each experimental session, the virtual sensor was placed directly adjacent to the top-left corner of the target (without overlapping it). It should be noted that the virtual sensor could not move beyond the edges of the workspace. No cues were given to participants when the virtual sensor became immobile at the borders of the workspace. The virtual sensor could, however, be moved again simply by a displacement away from the edge of the workspace. In order to determine which specific conditions facilitate the constitution and mastery of a new sensorimotor space, various motor commands were used to drive the device. In one condition (rotation), the virtual sensor could be moved by manipulation of a mouse and two keys on the keyboard. In another condition (keys), the participants moved the virtual sensor by pressing four keys on a keyboard. In a third condition (mouse), the virtual sensor was moved solely by manipulation of a mouse (see figure 2). Stimulus presentation was controlled by custom software written in Java 2.0.

Condition 1: rotation



Condition 2: keys



Condition 3: mouse

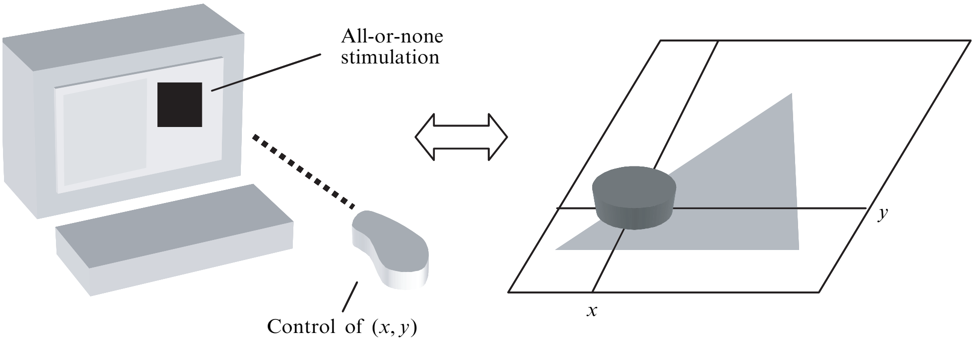


Figure 2. Schematic illustration of the device used in the experimental conditions: rotation, keys, and mouse.

2.1.2 *Participants.* Thirty participants took part in this experiment (sixteen females and fourteen males; mean age 22.8 years; range 19 – 27 years). All participants had normal or corrected-to-normal vision and reported normal auditory perception. Ten participants were allocated to each of the three device conditions (rotation, keys, and mouse). In each group, five participants were given auditory feedback, and five had visual feedback. The experiment took approximately 15 min to complete and was performed in accordance with the ethical standards laid down in the 1991 Declaration of Helsinki.

2.2 *Condition 1: Horizontal, vertical, and rotational displacement*

2.2.1 *Procedure.* Participants sat in front of a computer screen. The software described above was used with the following specifications. The virtual sensor could be moved by pressing one of two keys on a keyboard (the A and Z keys on the French 'AZERTY' keyboard arrangement) and by moving a mouse. The mouse determined only the displacement of the virtual sensor in a two-dimensional space. There was a one-to-one mapping between the displacement of the mouse and the displacement of the virtual sensor. The keys determined the direction in which the virtual sensor pointed in the space, with the A key eliciting a counterclockwise rotation and the Z key a clockwise rotation. Each key-press elicited a discrete rotation of 10°. This rotation was elicited independently of the position of the cursor. It should be noted that pressing the two keys simultaneously resulted in no rotation of the virtual sensor. The participants were not made aware of this. The sensory feedback changed whenever one or more pixels of the virtual sensor overlapped the target, but also whenever the virtual sensor was outside the target but pointed toward it. The orientation of the virtual sensor depended on the number of times that the key was pressed. In theory, therefore, the participants should have been able to link their actions to the sensory inputs which resulted from them. They should have obtained the impression of being either close to, or far from, the target as a function of the number of movements they needed to make in order to reach it.

The participants were informed that they could use the A and Z keys on the keyboard together with the mouse. The functioning of the device was not, however, explained to the participants. For half of the participants, the sensory feedback was visual, and for the other half it was auditory. The participants were given 5 min in which to freely explore the functioning of the device.(1) The participants were asked to comment on their impressions and hypotheses regarding the functioning of the device. At the end of the exploration period, the same experimenter asked the participants several questions in order to try and determine the nature and extent of their comprehension of the device: "What was the mouse used for?"; "What were the two keys on the keyboard used for?"; "What were the principles underlying the variations in colours/sounds?". If the participants had understood that the sensory feedback changed as a function of the exploration of a hidden form, they were then asked to specify if the variation occurred only when the virtual sensor was on the form or whether it also occurred when the virtual sensor was outside the form and pointing at it. The responses were not speeded and no further cues were given to the participants.

2.2.2 *Results.* The functioning of the rotational component of the device was not well understood by the participants. Seven out of the ten participants who took part in the study understood that the displacement of the mouse determined the displacement of a virtual sensor (four of the five participants who completed the experiment with visual feedback and three of the five participants who completed the experiment with auditory feedback). Comprehension of the displacement was often given by using an analogy with the displacement of a cursor. On the other hand, only two participants understood that the key on the keyboard determined the orientation of the virtual sensor (both participants completed the experiment with visual feedback). Five of the participants understood that the sensory feedback varied as a function of the presence of a hidden form in the workspace (three with visual feedback, two with auditory feedback). Only two participants (with visual feedback) understood that these variations took place when the virtual sensor pointed toward the hidden form and not only when it was actually on the form (see table 1). Overall, then, the majority

(1) Preliminary testing suggested that 5 min provided sufficient time for the participants to become acquainted with the experimental setup and to test their hypotheses.

Table 1. Number of participants who correctly responded, indicating that they had comprehended that their actions determined the displacement of a virtual sensor (Displacement), or that the sensory feedback varied as a function of their exploration of a hidden form (Object), for each condition (rotation, keys, and mouse), and for the two kinds of sensory feedback (auditory and visual). Each cell in the table corresponds to the response of five participants. For the rotation condition, there were two elements to the displacement: keys and mouse, and two levels of comprehension for the object: the sensory feedback varied as a function of the exploration of a hidden form (Object) and it varied when the virtual sensor was pointing toward the form (Target).

Condition	Displacement		Object	
	auditory	visual	auditory	visual
Rotation				
mouse	3	4		
key	0	2		
object			2	3
target			0	2
Keys	1	2	1	2
Mouse	4	5	4	4

of the participants understood the displacement of the mouse and its relation to the sensory feedback. However, very few of them understood the pointing function of the virtual sensor: They understood neither the functioning of the two keys on the computer keyboard nor the fact that the sensory feedback varied when the virtual sensor was pointing toward the target.

2.3 *Condition 2: Displacement controlled by the keyboard*

2.3.1 *Procedure.* In the keys condition, the experimental device was simplified by removing the pointing function of the virtual sensor in order to investigate whether this modification would facilitate participants' comprehension of the new sensorimotor space. The sensory feedback did not vary when the virtual sensor pointed toward the hidden form, but it did vary as a function of whether it was actually on the form or not. Four keys on a keyboard allowed the displacement of the virtual sensor. The four horizontally arranged keys on the keyboard (A, Z, E, R on the French 'AZERTY' keyboard) were used. The first two keys controlled the horizontal displacement of the virtual sensor; the other two keys controlled its vertical displacement. Each time a key was pressed, the device was displaced by 0.2 cm. The procedure was the same as in the previous condition. At the end of the exploration period, the participants were asked two questions in order to determine their comprehension of the device: "What were the four keys on the keyboard used for?"; "What were the principles underlying the variations in colours/sounds?".

2.3.2 *Results.* Only three of the participants understood that the manipulation of the keys resulted in the displacement of a virtual sensor (two of the five participants who performed the experiment with visual feedback and one of the five participants who performed the experiment with auditory feedback). These three participants also understood that the sensory feedback varied as a function of the presence of a hidden form situated in the workspace. Overall, very few of the participants understood the displacement allowed by the manipulation of the keys and its relation to the sensory feedback. It thus appeared that the condition in which the participants used the keys did not facilitate their comprehension of a new sensorimotor space as compared to the rotation condition.

2.4 *Condition 3: Displacement controlled by the mouse*

2.4.1 *Procedure.* In this condition, we tested the hypothesis that, as an exploratory movement, the displacement of a mouse is more natural than pressing the keys on a keyboard. Thus, the displacement of the virtual sensor was controlled by manipulation of a mouse. There was a one-to-one mapping between the displacement of the mouse and the displacement of the virtual sensor. The procedure was the same as in the two previous conditions. At the end of the exploration period, the participants were asked two questions in order to assess their comprehension of the device: "What was the mouse used for?"; "What were the principles underlying the variations in colours/sounds?".

2.4.2 *Results.* Nine out of the ten participants understood that the manipulation of the mouse controlled the displacement of a virtual sensor (all of the participants who completed the experiment with visual feedback and four out of the five participants who completed the experiment with auditory feedback). Eight of the participants understood that the sensory feedback varied as a function of the exploration of a hidden form (four with visual feedback and four with auditory feedback).

In order to determine whether participants' performance was significantly different across the three device conditions, paired t-tests were conducted on the number of correct responses by participants. It should be noted that for the rotation condition the answers were counted as correct when the participants understood correctly the functioning of both the keys and the mouse. As regards the understanding of a displacement with the virtual sensor, the analysis revealed significant differences between the mouse condition and the two other device conditions: rotation and keys (both ps < 0.01), but not between the latter two conditions ($p = 0.55$). Similarly, as regards the understanding of the object, the analysis revealed significant differences between the mouse condition and the other two device conditions: rotation and keys (both ps < 0.01), but not between the latter two conditions ($p = 0.59$). In addition, a t-test performed on the participants' responses as a function of the nature of the sensory feedback (visual versus tactile) failed to reach significance ($p = 0.09$).

2.5 *Discussion*

In this experiment, we investigated the critical factors necessary to establish the perception of a new sensorimotor space. In order to address this issue, participants used a novel device whose functionality had not been explained to them, and we tried to determine what they had understood about the device. In one condition, we investigated whether the participants would understand that their actions determined the displacement of the 'point of view' of a virtual sensor. When a hidden geometric form was targeted by the virtual sensor, all-or-none sensory feedback, which could be either visual or auditory, was presented to the participants. As regards the participants' understanding of their actions as corresponding to displacement in a simulated environment we found that although seven out of ten participants understood the functioning of the mouse, only two of them understood the pointing function of the device allowed by the manipulation of the keys. Similarly, even if half of the participants understood that the sensory stimulation varied as a function of the exploration of a form, only two of the participants understood that feedback was provided whenever the virtual sensor pointed toward the form and not only when it was on the form itself.

The inability of our participants to understand their actions as constituting a displacement in a simulated space and to think of their sensations as originating from their encounter with an object situated within this space may be due to the complexity of the linkage between participants' actions and the resulting pattern of sensory feedback. A similar hypothesis has been raised by Loomis (1992) in the case of virtual-reality devices. According to Loomis, participants' abilities to exteriorise the distal environment they interact with are correlated with the extent to which they can successfully model the linkage between their actions and the resulting sensory feedback. Loomis gives the example of the user of a teleoperator system who is controlling a 'slave robot' by means of a complex and unnatural but determinate interface (for instance, a musical keyboard). Until the user is able to represent the way in which the interface controls the robot, he/she will fail to experience externalisation of the environment within which the robot is situated. However, as Loomis points out, the representation of this linkage does not have to be accessible to conscious awareness, but can be understood as a functional organisation that operates independently of thought, in line with Piaget's (1936) notion of 'sensorimotor schema' (see also Mantovani and Riva 1999).

In a second condition, the displacement of the virtual sensor was achieved by pressing four keys on a keyboard. In this condition, few of the participants understood that the manipulation of the four keys resulted in the displacement of a virtual sensor in a simulated environment, and that the sensory feedback was determined by the exploration of a hidden form. Verbal reports by participants during the course of the experiment provided a window into their methods of exploration. The participants typically started by pressing the keys randomly, thereby inducing periodic colour or sound changes. For the majority of the participants, their first hypothesis involved a search for the key that gave rise to the white square on the screen (or a high-pitched tone), and which key, when pressed, resulted in a black square being presented on the screen (or a low-pitched tone). After realising that the pressing of a particular key was not always associated with a particular pattern of sensory feedback, their next hypothesis typically involved searching for the combination of keys that gave rise to each of the two kinds of sensory feedback. Only three of the participants searched for the law of reversibility of these changes and then subsequently searched for how the keys were linked together. These participants subsequently generated hypotheses concerning the keys and concluded that two keys were used for horizontal displacements and the other two for vertical displacements. These participants then went on to hypothesise that there was a form hidden within the workspace.

In a third condition, the displacement of the virtual sensor was elicited by the movement of a computer mouse. The manipulation of the mouse was easily understood as corresponding to the displacement of a virtual sensor. The participants frequently gave an analogy with the displacement of a computer cursor. The participants also found it easy to understand that the sensory stimulation varied as a function of the presence of a hidden form. However, these results could have been due to the participants' previous experience. That is, their previous use of a computer could have helped them to constitute the displacement of the mouse as corresponding to the displacement of a virtual sensor (cursor) on the screen. If this were to have been the case in our experiments, then we would have only modified the sensory feedback given to the participants. The conditions for the constitution of a new sensorimotor space are the same as those set up with Lenay's (2002) device. The results are similar: when participants' actions are already interpretable in terms of displacements, the participants can understand the sensorimotor space they are engaged with, even if the sensory feedback they have access to is unusual, and even if the sensory feedback does not in itself contain any spatial information. Furthermore, participants' performance was similar no matter whether the all-or-none sensory feedback was presented visually or auditorily. This result shows that the mastery of the experimental device used in the present study was based at the level of the information provided rather than at the level of the sensory modality used to provide that information.

3 Experiment 2: Form recognition in a simulated environment

In the second experiment we investigated the participants' mastery of a new sensorimotor space and, in particular, whether they could recognise simple geometric forms in a simulated environment.

3.1 *Method*

3.1.1 *Apparatus.* In this experiment, the same device and the same three conditions (rotation, keys, and mouse) as in experiment 1 (see figure 2) were used. In this second experiment we investigated whether participants' performance would be dependent on the nature of the sensory feedback that was provided to them. The sensory feedback could be either auditory (a high-pitched or low-pitched tone), or visual (a black or white square on the screen), varying as a function of the exploration of a hidden form in the workspace.

Furthermore, the visual feedback given to participants varied. During the first session, the participants had to recognise the hidden forms only by extracting the links between their actions and the resulting pattern of sensory feedback. During the second session, the participants were given an indication of their displacement in the simulated environment. In condition 1, an arrow was used whose position and orientation on the screen specified the position and orientation of the virtual sensor. For conditions 2 and 3, a small black circle on the screen was used that specified the position of the virtual sensor. For the sake of simplicity, this representation on the screen of the position of the virtual sensor was labelled 'visual representation'. We hypothesised that, thanks to this visual representation, participants would exhibit better control of their displacements of the virtual sensor and consequently that their abilities of form recognition would be facilitated.

3.1.2 *Participants.* The thirty participants who had taken part in experiment 1 subsequently completed experiment 2 with the same conditions of the device (ie rotation, keys, or mouse). Each participant completed two experimental sessions: first without, then with the visual representation of the position of the virtual sensor. On average, the two sessions took 20 min to complete.

3.1.3 *Procedure.* The participants were given an explanation of the functioning of the device. They were informed how the manipulation of the keys on the keyboard and/or the mouse would determine the displacement of a virtual sensor within a workspace; and how the sensory stimulation would vary as a function of their exploration of a hidden form within this workspace. The participants were asked to try and recognise six forms: three with visual feedback and three with auditory feedback, with the order of presentation counterbalanced across participants. The forms to recognise consisted of a set of three possible forms: a 4 cm × 4 cm square, a 4 cm diameter circle, and an equilateral triangle (4 cm in side length). The participants were instructed about the set of possible forms that they would have to try and recognise.

3.2 *Results*

An ANOVA was performed on the percentage of participants' correct recognition responses with three factors: the three-level between-group factor of condition of the device (rotation, keys, and mouse), the two-level factor visual representation of the virtual sensor (with versus without), and the two-level factor sensory stimulation (visual versus auditory). The results showed a significant main effect of the condition of the device ($F_{2,27} = 39.14$, $p < 0.0001$), and a significant main effect of the visual representation of the virtual sensor ($F_{1,27} = 15.13$, $p < 0.001$). A Duncan a-posteriori test revealed significant differences between the three conditions of the device (rotation, keys, and mouse; all $p\text{s} < 0.001$). The analysis did not show any significant main effect of sensory stimulation ($F_{1,27} < 1$, ns), nor any interaction between condition and visual representation, between condition and sensory stimulation, or between visual representation and sensory stimulation (all Fs < 1).

Of the three conditions of the device, the keys condition gave rise to the more accurate performance (mean: $0.80 \pm$ SD of 0.28) followed by the mouse condition (0.62 ± 0.23), and then the rotation condition (0.28 ± 0.16). Concerning visual representation, participants' performance was better with a visual representation of the position of the virtual sensor (0.64 ± 0.21) than without it (0.49 ± 0.21) (see table 2 and figure 3). However, it should be noted that all of the participants completed the session without the visual representation before the session with the visual representation of the virtual sensor, and so we cannot rule out the possibility that practice may have played some role in the visual representation effect.

Table 2. Mean percentage of correct responses for each condition—rotation, keys, and mouse—(±SD) and for the two types of sensory feedback: auditory and visual.

Session	Rotation	Keys	Mouse	Mean
Without visual representation				
auditory	26.6 (±14.0)	70.0 (±29.2)	53.3 (±28.1)	49.4 (±23.0)
visual	23.3 (±16.1)	76.6 (±27.4)	46.6 (±23.3)	
With visual representation				
auditory	30.0 (±29.1)	83.3 (±17.6)	70.0 (±24.6)	64.4 (±21.9)
visual	33.3 (±27.2)	90.0 (±16.1)	80.0 (±17.2)	
Mean	28.3 (±21.6)	80.0 (±22.6)	62.5 (±23.3)	56.9 (±22.4)

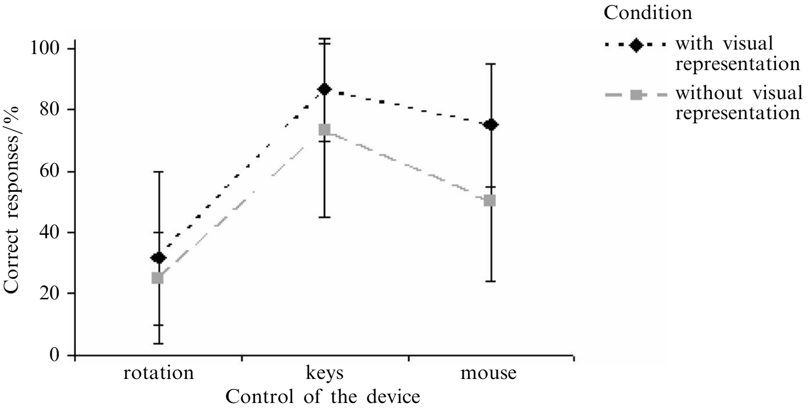


Figure 3. Percentage of correct responses obtained over the experimental conditions—rotation, keys, and mouse—for the session without visual representation, and the session with visual representation. The results from the visual and auditory feedback conditions were averaged. The means were taken over all participants. The error bars represent the standard deviation of the mean.

3.3 *Discussion*

In experiment 2, we investigated the conditions necessary for participants to acquire the mastery of a new sensorimotor space when their motor commands and the sensory feedback were modified. The participants were provided with a minimalist device and we studied their form-recognition abilities in a variety of different experimental conditions.

When the displacement of the virtual sensor was determined vertically, horizontally, and in rotation (condition 1), the participants were unable to recognise the forms hidden in the workspace. At one level, it might be thought that the poor performance observed in this condition was attributable to the artificiality of the device. Bach-y-Rita et al's (1969) and Lenay's (2002) experiments were conducted in a real environment, in which the representation of the body was already established. The only modification introduced in their studies concerned the nature of the sensory feedback that was provided. Thus, the space of displacement of participants was already *acquired*, *consistent*, *and continuous*. By contrast, in the two experiments reported here, the representation of the space of displacement was not *acquired*. Participants had to learn new motor commands: the manipulation of the mouse and keys on the keyboard. This representation was not entirely *consistent*. As sensory inputs, we took into account only the auditory or visual stimuli generated by our software, but the participants may also have paid attention to other sensory inputs that may have seemed important to them, such as any proprioceptive information deriving from the manipulation of the mouse and keys. This proprioceptive information would not have been identical to that obtained with a corresponding displacement in a natural environment. Thus, the mastery of this device cannot immediately rely on proprioceptive feedback. The representation of the displacement space was not *continuous*. This is due to the artificial functioning of the mouse which had no effect when it was, for example, lifted off the table. The user's point of reference is the first point of contact of the mouse with the table. Furthermore, the visual coordinates are limited by the constraints imposed by the screen, which is not the case for an arm movement, for example.

In our everyday use of a computer, we are not usually bothered by these limitations. In general, regular use of the mouse needs no cognitive intervention and the use of the mouse leads to a kind of exteriorisation: we have the impression of moving the cursor, not the mouse. Presumably this difference with the conditions of our experiment derives from the fact that, in normal computer use, the cursor representing the position of the mouse is continuously visible. Consequently, we expected that, if we provided participants with a visible representation of the position of the virtual sensor and the control of their displacements, their ability to recognise forms should have been facilitated. This was not the case. Regardless of whether the participants had access to a visual representation of the position of the virtual sensor, their performance remained very poor (31.6% correct recognition with visual representation as compared to 25.0% without).

At least three hypotheses can be put forward to try and explain the poor performance of participants in this condition. First, the unnatural situation may have slowed the process of mastering the device. If this had been the case, allowing a more extended learning period might have improved participants' performance. Second, the manipulation of the two keys on the keyboard could have prevented participants from mastering this device: the use of horizontally arranged keys on a keyboard does not correspond to what is usually associated with rotation. In this case, the artificiality of the device may have prevented participants from basing their new learning on previously established corporal schemas, and thus prevented them from extracting a correspondence between the new sensations and their previously acquired notions of body and space. Third, the lack of precision of the displacement of the mouse could have been responsible for the fact that participants were unable to abstract a sufficiently precise law of co-variation between their action and the resulting patterns of sensory stimulation. The other two variations of the devices (where the displacement of the virtual sensor was determined by pressing four keys on a keyboard or by the manipulation of a mouse) allowed for a better comprehension whether, in the first condition, the participants' inability to master this new sensorimotor space was due to lack of learning, the artificiality of the manipulation of the keys, or the lack of precision of the displacement of the mouse.

When the displacement of the virtual sensor was determined by pressing the keys on the keyboard, participants easily recognised the hidden forms in the workspace. Participants' verbal reports during the experiment allowed us to understand the methods they used when there was no visual representation of the position of the virtual sensor. To recognise the form, participants primarily used an edge-scanning strategy. When participants were 'lost', they tried to find an edge again but they had the feeling that they had to reinitiate their exploration. Some participants recognised the hidden form by a kind of step-by-step mental reconstruction of the form. Others applied a deduction directly linking their movements to the sensory feedback. For example, participants clearly understood that, when the two directions of movement (vertical and horizontal) were reversible at the same spot, they were at a corner. Similarly, when the participants observed that in order to follow the edge they must make two vertical displacements for each horizontal one, they inferred they were on a line globally oriented at 30° from the vertical. Thus, participants were able to acquire the mastery of a new sensorimotor space when we modified their means of action and the sensory feedback that they had access to. These results show that the precision of the sensorimotor law is essential for form recognition. The participants could manage this task by abstracting the law of co-variation, even if their movements were neither natural nor linked to any previously established schemas.

When the displacement of the virtual sensor was determined by the manipulation of a mouse, participants managed to recognise the hidden forms in the workspace but with less precision than those who used the keys on the keyboard. It thus seems that the manipulation of a computer mouse is less precise than the use of the keys on a keyboard. This lack of precision could have prevented our participants from establishing a sufficiently precise law of co-variation between their action and the resulting sensory stimulation.

4 General discussion

Our aim was to investigate here conditions that are necessary for users of a new technical device to reach distal attribution under conditions where they were not told anything about the apparatus beforehand. In the first experiment we addressed this issue by investigating across three different technical devices (rotation, keys, and mouse) the conditions under which the participants understood their actions as constituting a displacement in a simulated space and their sensations as originating from the encounter with an object situated within this space. In the second experiment we investigated participants' abilities to recognise simple forms with the use of the same device. The object of this experiment was to determine whether distal attribution was correlated with the accuracy of exploration allowed by the manipulation of the device.

The main result to emerge from this study is that when the participants' actions are interpretable in terms of displacement (which is the case when using a mouse but not when using the keys of a keyboard) they readily infer that their actions correspond to a spatial displacement and that their sensations originate with the encounter with an object situated in this space. Thus, in contrast to the results reported by Epstein et al (1986), we were able to show that distal attribution can occur when the participants use a sensory-substitution device without being aware that they are using one. The difference between Epstein et al's results and those reported in the present study may be due to the fact that manipulation of a computer mouse is a more natural means of exploration than the use of a lever. In addition, our results complement those of Hardy et al (2000). Although participants can reach distal attribution when the sensory stimulation provided to them does not contain any spatial information, they manage to do so only when the space of displacement allowed by the device corresponds to a previously acquired space of displacement (ie the use of a mouse versus the use of keys). In addition, the results of the second experiment revealed that participants' abilities to reach distal attribution are not linked to the precision allowed by the device. Indeed, distal attribution was reached more often through the use of the mouse than through the use of the keys of the keyboard, whereas performance in form recognition was better when the participants used the keys than when they manipulated the computer mouse.

The second main result to emerge from our study was that, across all the experimental conditions, participants' performance was unaffected by the nature (ie modality) of the sensory feedback (auditory or visual) that was provided. This corroborates the predictions of sensorimotor theories of perception (eg Noë 2005; O'Regan 1992; O'Regan and Noë 2001). According to the sensorimotor theory, sensation derives not from sensory input itself, but from the rules that govern action-related changes in sensory input. As a consequence, the same sensation should be obtained via two different channels (here visual and auditory), provided the laws of co-variation that are involved are the same. However, the fact that there was no difference between sensations derived from auditory and visual feedback in our experiments could also be due to the all-or-none character of the stimulation. With this all-or-none stimulation, it may be that the participants learned a kind of grammar (or rather alphabet) which was the same for both sensory modalities, and then established a kind of deduction, rather than actually feeling a 'sensation'.

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