Effects of visual deprivation on space representation: Immediate and delayed pointing toward memorised proprioceptive targets

Florence Gaunet
LIMSI-CNRS, Bat 508, BP 133, 91403 Orsay, France; e-mail: gaunet@mnhn.fr

Yves Rossetti
Espace et Action, INSERM UMR 534, 16 avenue doyen Lépine, 69500 Bron, France

Received 9 July 2004, in revised form 16 February 2005; published online 16 November 2005

Abstract. Congenitally blind, late-blind, and blindfolded-sighted participants performed a pointing task at proximal memorised proprioceptive targets. The locations to be memorised were presented on a sagittal plane by passively positioning the left index finger. A 'go' signal for matching the target location with the right index finger was given 0 or 8 s after left-hand demonstration. Absolute distance errors were smaller in the blind groups, with both delays pooled together; signed distance and direction errors were underestimated with the longer delay, and were overestimated by blind groups, whereas the blindfolded-sighted group underestimated them. Elongation of the scatters was stretched but not affected by delay or group. The surface scatter was greater with the longer delay; and orientation of the main axis of the pointing ellipses shows the use of an egocentric frame of reference by the congenitally blind group for both delays, the use of egocentric (0 s) and exocentric (8 s) frame of reference by the blindfolded-sighted group, with the late-blind group using an intermediate frame of reference for both delays. Therefore, early and late visual-deprivation effects are distinguished from transient visual-deprivation effects as long-term deprivation leads to increased capabilities (absolute distance estimations), unaltered organisation (for surface and elongation), and altered organisation (amplitude and direction estimations, orientation of pointing distribution) of the spatial representation with proprioception. Besides providing an extensive exploration of pointing ability and mechanisms in the visually deprived population, the results show that cross-modal plasticity applies not only to neural bases but extends to spatial behaviour.

1 Introduction
In this paper we address the role of visual experience in the spatial abilities of adults. The obvious reliance of brain development and behaviour on sensory experience has been previously recognised (see Bavelier and Neville 2002; Kujala et al 2000; Rauschecker 2002). In fact, behavioural and brain reorganisations take place after long-term sensory deprivation, and often lead to compensatory plasticity in the processing of spared modalities between experimental groups, ie to cross-modal plasticity (Bavelier and Neville 2002).

When examining the extent to which the properties of cognitive processing rely on sensory or sensorimotor experience, one method is to observe the effects of the age of onset of sensory deprivation in adults, ie to perform comparisons between early or congenital versus late onset of blindness, and late onset versus transient deprivation. We combined these two approaches to determine to what extent the spatial behaviours are the result of the experience of a particular sensory modality. The present study was directed towards evaluating the role of experience with the visual sensory modality.

1.1 Spatial processing and visual experience
To date, it has not been possible to formulate a general model that would account for the effect of visual deprivation on spatial behaviour. Indeed, early and long-term visual deprivation does not seem to have a consistent effect on spatial behaviour (see Thinus-Blanc...
and Gaunet 1997). Published data present an analysis only of absolute distance and direction errors, whereas constant and variable errors have been rarely reported. In addition, spatial strategies have seldom been studied (Gaunet et al. 1997; Gaunet and Thinus-Blanc 1996). Consequently, there is evidence for both deficient and effective spatial behaviour in early-blind participants as compared with visually experienced subjects. Surprisingly, blind subjects appear to perform better than blindfolded-sighted subjects in some of the spatial tasks (Thinus-Blanc and Gaunet 1997). Additionally, published data reveal that early-blind and congenitally blind participants were involved in different ways and that, furthermore, young blind people may have been raised very differently (in terms of sensorimotor and intellectual stimulation) (Millar 1994; Thinus-Blanc and Gaunet 1997). Finally, various spatial tasks have been used (see Thinus-Blanc and Gaunet 1997), each involving the use of very different spatial frames of reference. These factors may explain part of the inconsistency found in the literature. Accordingly, we chose to investigate whether spatial frames of reference involved in the performance of spatial tasks may explain the discrepancies observed previously, by testing congenitally blind rather than early-blind adults.

A commonly accepted notion is that spatial frames of reference are organising systems supporting spatially oriented behaviours. Two main frames of reference have been distinguished: the egocentric and exocentric (or allocentric) ones (Bridgeman 1991; Paillard 1987, 1991; Rossetti 1998). In the former, individuals rely on body-centred coordinates to encode positions, and in the latter, they use external landmarks (see also Millar 1994). This notion of frame of reference was introduced in the seventies to interpret animal spatial behaviour, and has been extensively used for interpreting child and adult spatial cognition in large-scale environments [see Millar (1994) and Gaunet and Thinus-Blanc (1997) for reviews]. More recently, in the proximal space, egocentric and exocentric spatial frames of reference have been seen as organising systems supporting spatially oriented behaviours, such as pointing toward targets (i.e., locating targets on a fixed array) (Andersen and Buneo 2002; Desmurget et al. 1998).

Since previous attempts have been unsuccessful in determining and providing an extensive list of frames of reference and the effects of visual deprivation on spatial behaviour (Thinus-Blanc and Gaunet 1997), we investigated the role of different types of visual deprivation in a task known to involve egocentric and exocentric spatial frames of reference, namely pointing towards or locating memorised proprioceptive targets after a 0 s and an 8 s delay [for a preliminary study comparing congenitally blind and blindfolded-sighted participants, see Rossetti et al. (1996)].

1.2 Spatial frames of reference and visual experience

Pointing is a crucial behaviour for assessing the role of vision as it is strongly controlled by vision in sighted persons (Bridgeman 2000; Coello and Magne 2000; Rossetti 1998; Rossetti and Pisella 2002). Surprisingly, except for early developmental assessment purposes, pointing in blind populations has seldom been studied. Early-blind children rely mainly on an egocentric frame of reference for memorising the location of objects located on a table (Millar 1979, 1981, 1985). Experiments involving spatial processes in manipulatory space led Millar (1994) to propose that early visual experience helps in the use of external cues as reference anchors (exocentric encoding). According to Millar (1994, pages 142–153), blindfolded-sighted participants are more likely to assess the spatial relationships between distal spatial cues and understand exocentric spatial coordinates, which are more obvious in vision than through the other senses (see also Gaunet et al. 1997). Related to this hypothesis is the fact that the early blind have never experienced a large number of places within a short time range. This may therefore reduce their understanding of space. Places exist and maintain spatial relationships even though they are not within reach. Early visual experience would thus facilitate involvement of an overall representation of space (Millar 1994).
To our knowledge, very few studies have been conducted to test pointing abilities for movement reproduction in blind adults. In the first study (Colley and Colley 1981), early-blind and late-blind people had to reproduce, in the horizontal plane, end-location and distance of preselected arm movements of two different amplitudes (≈30° and 60°). This study confirmed that the late blind reproduce both distance and end-location better than the congenitally blind. DiZio and Lackner (2000) examined whether congenitally blind and sighted participants demonstrate adaptation to Coriolis force when they pointed to previously memorised haptically specified target locations before them. The groups did not differ significantly on any performance measure, ie lateral-endpoint and absolute-distance errors, but only one target position was used. First, we observe that these two experiments focused only on quantitative variables, and although absolute error is the single best accuracy index, it is composed of constant and variable errors (Schutz and Roy 1973). Second, the effect of visual deprivation is not consistent in the two experiments. Pointing by persons who are blind requires further investigation, as it is a good model to study the involvement of vision (Rossetti et al 1996). Note that the present study involved pointing in reachable space.

1.3 Different delays in pointing for dissociating egocentric and exocentric spatial frames of reference

Studies involving goal-directed actions towards proprioceptively or visually memorised targets can help us understand the nature of brain mechanisms and spatial representation. Indeed, proprioceptive pointing is an easy and simple way to operationalise different types of spatial representations and their underlying mechanisms (Paillard 1987, 1991), ie cognitive (exocentric) versus sensorimotor (egocentric) encoding of spatial information. Experiments strongly suggest that the spatial knowledge expressed within a short delay following stimulus presentation relies on egocentric representations, and that the representation expressed after a longer delay following stimulus presentation relies on an exocentric representation, ie dissociation.

In the first experiment (Rossetti et al 2000; described by Rossetti 1998, and Rossetti and Pisella 2002), visual targets were briefly presented on a computer screen (frontal plane). In the course of different sessions, two different arrays of 9 targets (displayed along a horizontal arc and a vertical line) were used. Participants were required to accurately point their right hand toward the target location when a ‘go’ signal was given, ie between 0 and 8 s following target presentation (0, 0.5, 1, 2, 4, and 8 s). Between trials, the right hand rested on a starting place located by a tactile cue, at the bottom of the screen. The pointing distribution was analysed. When the delay was less than 1 s, the main axis of the pointing distribution tended to be more aligned with movement direction, whereas after an 8 s delay, the main axis of the pointing distribution, β, tended to be aligned with the target array (displayed along a horizontal arc and a vertical line), and thus became dependent on the visual context provided by the experimental design. Distinct spatial frames of reference are therefore used, depending on the delay. Movements are encoded in an egocentric reference frame centred on the hand for immediate responses, whereas after a delay they are encoded in the exocentric space. Because the alignment effect on the target array is found for both target arrays (a horizontal arc and a vertical line), there is a strong case for inferring that different frames of reference are involved.

A second experiment was designed to determine whether these findings were a function of the sensory modality (Rossetti and Régnier 1995). For a broader generalisation of the findings obtained with vision, targets were proprioceptively defined in the sagittal plane in this study. Blindfolded-sighted participants had to use their left hand to encode the position of places in a space displayed in the sagittal plane.
The targets were positioned along a horizontal arc. After a delay of 0 and 8 s, the participant had to reach the position with his/her right hand. The spatial distribution of pointing responses tended to be aligned with the target array used in the experiment (along a horizontal arc). Interestingly, this effect was observed only when the target location had to be memorised (8 s delay), but did not occur when the participant was asked to point immediately after target encoding (0 s delay). As a control, Rossetti and Régnier conducted the same experiment, but with targets located along a vertical line. Again, the spatial distribution of pointing was aligned with the target array used in the experiment (along the line) for the longer delay. These findings suggest that the internal representation of target location used to produce an aiming movement toward a memorised proprioceptive target was related to a representation of the whole target array, whereas this did not appear to be the case for immediate pointing (see also, Rossetti 1998; Rossetti and Procyk 1997). Rossetti et al (1996) also replicated this finding with five blindfolded-sighted participants. Additionally, evidence of specific involvement of exocentric cues in delayed tasks was also obtained by Zuidhoek et al (2003) for haptic orientation-matching task.

To conclude, this set of experiments suggests that during visual and proprioceptive encoding, with a 0 s delay, an egocentric (or sensorimotor or pragmatic) representation tends to be used for goal-directed action, whereas an exocentric (or cognitive) representation tends to be used for the longer delay.

1.4 The present study

The above review allows one to argue that the activation of egocentric versus exocentric frame of reference can be controlled by the delay used for a pointing response. As this effect has been described not only in the visual domain but also for proprioceptive targets, it may provide a valuable tool in the determination whether early and long-term visual deprivation affects the underlying spatial frames of reference.

The available literature on blind adults is rather limited and focuses only on overall error parameters. Using the same task as Rossetti and Régnier (1995) and Rossetti et al (1996), we explored pointing movements made by groups of congenitally blind, late-blind, and blindfolded-sighted adult participants, with the aim of investigating the reference frames used to perform the task (ie the type of space representation involved). In comparison with the preliminary study (Rossetti et al 1996), all new congenitally blind and blindfolded-sighted individuals were tested and the group sizes (originally five per group) were increased (by eight and two participants, respectively), and a group of nine late-blind participants was included in order to investigate the whole issue of the effect of visual experience.

As mentioned before, the effect of visual experience on spatial processing is not reliable across studies. However, according to Millar’s studies, a reliable feature is that early-blind children consistently exhibit difficulties in setting up an exocentric frame of reference. Consequently, early-blind and blindfolded-sighted participants may exhibit different patterns of pointing distribution for the orientation of a memorised target; it may also be predicted that movements aimed at memorised and not memorised target locations will lead to similar main-orientation-axis pointing distributions in early-blind participants, because they may tend to use an egocentric frame of reference (see also Rossetti et al 1996). The remaining question is about the pointing distribution produced by the late-blind individuals who were never tested before.

The second aim of this study was essentially descriptive, ie to characterise pointing, according to different types of visual deprivation (or visual status). For this purpose, a detailed analysis of pointing-distribution parameters gives a clearer depiction of pointing in the three groups; they are accounts of the alternative developmental pathways that blindness may engender.
2 Material and methods

In this experiment we compared three groups with a different visual status locating (or pointing at) proprioceptive targets, one at a time, on a fixed array according to two delay instructions.

2.1 Participants

Three groups of participants were involved in the experiment. They were not the same as the ones involved in the Rossetti et al (1996) study. The congenitally blind group (CB) consisted of thirteen right-handed participants (six females and seven males). There were two cases of optic nerve degeneration, two of microptalmia, three of retinoblastoma, four cases of glaucoma, and two cases were undetermined. They had become blind before the age of 12 months. The group ranged in ages from 20 to 46 years (mean = 32.6 ± 8.8 years). The late-blind group (LB) consisted of nine right-handed participants, five females and four males. They had all become blind through accidents (road, sports, or occupational) after the age of 4 years. The group ranged in ages from 23 to 45 years (mean = 33.3 ± 7.98 years). The minimum spell without sight was 7 years, and the maximum was 35 years (21 years on average). The control group was composed of seven sighted participants, matched in age, sex, and handedness (from 22 to 45 years of age, mean = 30.85 ± 8.41 years). These participants (BS) were blindfolded prior to entering the experimental room.

All blind participants were totally blind, with no neurological disease. We ascertained by a preliminary questionnaire that blind participants were raised in a similar way, ie they had not been overassisted by their family, their family stimulated them, and they were engaged in activities early in life. Congenitally blind participants lost their sight in both eyes in their first year; we considered late-blind participants as those who had had normal sight during the first three years, and the onset of blindness was determined when blindness affected both eyes. They were recruited with the assistance of institutions dedicated to ‘Education for the Blind’ and its associations. All led autonomous lives in their communities. Most of them were employed or were university students. Before the experiment, all were informed of the general method (ie pointing) but were naive about the specific hypotheses. We provided an explanation of the experiment and obtained informed consent.

2.2 Material

The pointing device was a transparent sagittal plane fixed upon a table. Participants were seated in front of this plane (figure 1a), with their left hand resting on the table. Participants were not informed about the specific hypothesis of the study.

![Figure 1](image_url)

**Figure 1.** (a) Apparatus: the left hand (passive hand) is placed on the table and the right hand (active hand) is placed on a tactile mark affixed to the bottom of the panel (starting position). The index finger of the left hand is put by the experimenter on the target and then back on the table; computer tones are triggered manually by the experimenter, to signal the moment when the participant has to point toward the memorised target. (b) Spatial configuration of the target array. Targets are arranged along an arc centred on the starting position of the finger.
and the right hand placed on a tactile mark affixed to the bottom of the panel (starting position). Six targets were defined on the panel along an arc centred on the starting position (30 cm radius) (figure 1b). The targets were identified on the screen with a pencil mark. With respect to the vertical axis, the targets were located from $17^\circ$ toward the participant ($-17^\circ$) to $43^\circ$ away from the participant ($+43^\circ$) in 12° steps. A transparent millimetre sheet was placed on the right side of the panel, with respect to the participant, and kept in place with paper taped along the edges of the panel. It allowed the recording of position of the spots touched by the participant. Pointing was performed with the fingertip.

### 2.3 Procedure

The sighted participants were blindfolded before being exposed to the experimental device and then throughout the experiment. The procedure was identical for the three groups. During the familiarisation phase, the participants were acquainted with the apparatus and the procedure. They were able to freely explore the apparatus with both hands and the locations of the six targets were presented to the participants by the following procedure. These locations were visible only to the experimenter and no tactile cue was available to the subjects. Target location encoding was performed by a passive demonstration with the left target-index finger raised from the table and left on the target location: the experimenter took hold of the participant’s left hand and moved it to the target position and returned the left hand to its initial position. The participants were then instructed to perform a right-hand movement to the target location. The left target-hand was then moved back to the table by the experimenter, and the participant was asked to put his/her right hand back on the tactile mark affixed to the bottom of the panel (starting position). The order of presentation of the targets was from the closer to the farther targets, and the six targets were pointed at six times.

During the testing phase, the same procedure was used, except that a delay was introduced between target encoding and the right-hand response towards the target. Target location encoding was performed by a passive demonstration with the left index finger raised from the table; it stayed on the target location for 300 ms, and then immediately moved back to the table. A 300 ms computer-generated low tone allowed the investigator to keep this duration constant. After the demonstration, a high tone was used to instruct the participants to perform a right-hand movement to the target location. The task consisted of pointing with the right index finger and touching the vertical plane in the most accurate position. No constraint was imposed on the pointing-arm posture, and care was taken to avoid an uncomfortable passive-arm posture that could bias pointing (Rossetti et al 1994a). Pointing had to be performed within a 1.5 s time window; the maximum trial duration (1.5 s) was signaled by a second high tone. No correction was allowed once the finger touched the screen. Two delays between target demonstration and ‘go’ signal, 0 and 8 s, were used in random order. The vertical plate was thick enough to prevent tactile–tactile cues. The six target positions and the two delay periods were randomly presented. Each participant performed ten pointing responses for each combination of target position and delay. Each individual session thus included 120 pointing responses. Pointing coordinates were collected. The position of the very end of the fingertip was recorded. The accuracy of recording was 1 to 2 mm; this was previously checked with a touch screen.

### 3 Data analysis and hypotheses

The endpoint recording of each individual movement was used to compute several variables. Figure 2a defines the variables $d$ (absolute distance error), $R_0$ (movement amplitude error), and $z$ (direction amplitude error), and figure 2b shows the ellipse surface $s$ (in grey), minor and major axis lengths [ie smaller and larger dimensions of the
pointing-distribution ellipse, respectively, to compute $r$ (the major-to-minor axis length ratio), and $b$ (ellipse major axis orientation). We provide descriptions of these parameters below, and we formulate predictions of the effects of group and delay factors on the main parameters, in particular with respect to the Rossetti et al (1996) pointing study which involved five congenitally blind and five blindfolded-sighted subjects.

3.1 Constant errors

Constant errors provide information on systematic biases. Movement encoding processes and deviation of the mean endpoint from the target—as the output of a sensorimotor transformation—may demonstrate the presence of bias in the internal representation of movement and target position encoding, ie the coordinate system used.

Constant errors were measured along movement direction [movement direction error, $\alpha$ (°)] and in movement amplitude [movement amplitude error, $R_0$ (mm)], relative to the ideal reach that would hit the target. Angles were given a negative sign when the reach was closer to the body than the aimed target, and amplitude errors were given a negative sign when movement distance was shorter than the ideal reach. Group and delay factors are supposed to affect these two variables, if indeed visual experience is used to calibrate movement encoding (Millar 1994) and according to Rossetti et al’s previous studies on pointing, respectively. Finally, it can be expected that depth perception (movement direction error) will be affected in the congenitally blind group (Arditi et al 1988). A comparison of this variable between groups provides information whether visual experience accounts for movement calibration upon vision.

3.2 Absolute error

The absolute distance error, $d$ (in mm), is the unsigned mean distance between pointing and target. Although the so-called absolute error is a non-specific parameter affected by both constant and variable factors (Schutz and Roy 1973), its value was computed to allow comparison with previous studies. Because this parameter is a compound of both constant and variable parameters, it is difficult to produce clear predictions about its variation.

**Figure 2.** Computation of dependent variables. The larger black circle represents the target and the smaller black circles represent attempts to proprioceptively match the black cross target. (a): $d$, absolute distance error between pointing distribution and target; $\alpha$, movement amplitude error of the pointing distribution; $R_0$, movement direction error of the pointing distribution. (b): Minor and major axes length of pointing distribution; $\beta$, orientation of the ellipse major axis.
3.3 Variable errors

The three variables—ellipse surface area, major-to-minor axis length ratio, and ellipse major axis orientation—provide information on the 2-D pointing distributions.

Variable error was assessed by confidence ellipses (95%) of the scatter of fingertip positions (ie mean ±1.96 SE). The main parameters of the confidence ellipses were computed.

The ellipse surface area, \( s \) (mm\(^2\)), provided an estimate of the overall pointing variability, and was thus expected to increase with the longer memory delay, and to be higher in the BS group (Rossetti et al 1996).

The lengths of the minor and major axes of the pointing distribution are given by the variable minor axis length and major axis length (mm), respectively. The ratio of the two lengths (major-to-minor axis length ratio) provides an estimate of the ellipse morphology, ie elongation. The greater the ratio, the more elongated the ellipse. No effects of group or of delay on this ratio were expected according to the results of Rossetti et al (1996).

The ellipse major axis orientation (\( \theta \)) was computed relative to mean movement direction. According to previous experiments (Rossetti 1998; Rossetti et al 1996; Rossetti and Régnier 1995), this orientation should be affected by the delay period in blindfolded-sighted participants, in such a way as to become aligned with the target arc, only after the 8 s delay, but not in the congenitally blind group, irrespective of the delay, if indeed this group has difficulties in using an exocentric spatial framework (Rossetti et al 1996).

In order to show the strength of local distortion (or the involvement of egocentric or exocentric representations), we focus on both the ratio of the lengths of the two main axes (ellipse elongation), and on the orientation of the main axis (alignment of the direction of the pointing distribution, according to movement direction—egocentric encoding, and target array—exocentric encoding).

All variables were submitted to a mixed two-way (group × delay) analysis of variance (ANOVA, Statistica\textsuperscript{©} version 5.5), with delay as repeated measures and group as a between-subjects variable. The values of the six targets were averaged. The values presented in the results section are the means ± standard errors computed on thirteen values for the congenitally blind (CB) participants, nine values for the late-blind (LB) participants, and seven values for the blindfolded-sighted (BS) participants, respectively. Planned comparisons were also conducted.

4 Results

Table 1 shows the values of the six variables (means and standard errors) obtained for each delay in each group, and a summary of the ANOVA data. Surprisingly, the results show that the effects of visual status and delay differ depending on the parameters analysed: overall, the delay effect is more pronounced in visually experienced participants; the effect of early visual deprivation is less pronounced than expected (ie overall, congenitally blind and late-blind participants perform more similarly than the visually experienced group), and having been trained to process space without vision improves absolute distance estimation.

To visualise the pointing distributions according to the delay and the group, figure 3 shows the confidence ellipses of the movement endpoints obtained for one representative participant from each group, for the two delays. First, whatever the experimental condition, the ellipses are elongated, as shown further by the inspection of the major-to-minor axis length ratio. Second, for the blindfolded-sighted participant, the main orientation of the ellipse obtained for the 0 s delay tended to be aligned with movement direction. For the 8 s delay, the ellipses tended to be elongated along the target array, ie orthogonal to movement direction. The congenitally blind participant exhibited similar
Table 1. Mean (upper line) and standard errors (lower line, in italics) observed for each of the six combinations: group (CB, LB, BS) × delay (0 s, 8 s), for variable errors (ellipse surface area, $a$; major-to-minor axis length ratio, $r$; major axis orientation, $\beta$), constant errors (movement amplitude error, $R_0$; movement direction error, $\alpha$) and absolute distance errors, $d$. ANOVA results are presented in the bottom three lines for the group, delay, and group × delay effects. Values of $F$ are shown in plain fonts, and the corresponding probabilities ($p$) in italics in the lower line.

<table>
<thead>
<tr>
<th>Group</th>
<th>Delay/s</th>
<th>$d$/mm</th>
<th>$s$/mm$^2$</th>
<th>$r$</th>
<th>$\beta$/°</th>
<th>$\alpha$/°</th>
<th>$R_0$/mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>CB</td>
<td>0</td>
<td>46.07</td>
<td>1236.89</td>
<td>2.16</td>
<td>132.86</td>
<td>4.06</td>
<td>20.89</td>
</tr>
<tr>
<td></td>
<td></td>
<td>± 29.23</td>
<td>± 1399.15</td>
<td>± 0.55</td>
<td>± 16.72</td>
<td>± 4.22</td>
<td>± 34.25</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>45.33</td>
<td>1633.83</td>
<td>1.90</td>
<td>139.13</td>
<td>2.91</td>
<td>15.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>± 28.58</td>
<td>± 947.64</td>
<td>± 0.35</td>
<td>± 19.14</td>
<td>± 5.18</td>
<td>± 31.21</td>
</tr>
<tr>
<td>LB</td>
<td>0</td>
<td>58.31</td>
<td>949.41</td>
<td>2.05</td>
<td>121.21</td>
<td>5.15</td>
<td>33.56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>± 29.83</td>
<td>± 418.29</td>
<td>± 0.52</td>
<td>± 22.12</td>
<td>± 7.31</td>
<td>± 18.80</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>53.69</td>
<td>1468.12</td>
<td>2.20</td>
<td>120.67</td>
<td>3.90</td>
<td>21.96</td>
</tr>
<tr>
<td></td>
<td></td>
<td>± 25.48</td>
<td>± 542.63</td>
<td>± 0.72</td>
<td>± 16.09</td>
<td>± 6.82</td>
<td>± 23.12</td>
</tr>
<tr>
<td>BS</td>
<td>0</td>
<td>106.90</td>
<td>845.22</td>
<td>2.10</td>
<td>135.19</td>
<td>4.44</td>
<td>48.96</td>
</tr>
<tr>
<td></td>
<td></td>
<td>± 46.91</td>
<td>± 209.55</td>
<td>± 0.54</td>
<td>± 22.63</td>
<td>± 4.08</td>
<td>± 14.68</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>103.80</td>
<td>1568.88</td>
<td>2.24</td>
<td>110.15</td>
<td>7.58</td>
<td>58.73</td>
</tr>
<tr>
<td></td>
<td></td>
<td>± 43.60</td>
<td>± 505.15</td>
<td>± 0.20</td>
<td>± 14.02</td>
<td>± 7.76</td>
<td>± 18.25</td>
</tr>
</tbody>
</table>

Group effect
\[ F = 8.08 \quad p < 0.01 \]
\[ F = 1.04 \quad p = 0.31 \]
\[ F = 0.19 \quad p = 0.82 \]

Delay effect
\[ F = 18.19 \quad p < 0.001 \]
\[ F = 2.93 \quad p = 0.09 \]
\[ F = 5.94 \quad p < 0.01 \]

Group × delay
\[ F = 8.61 \quad p < 0.005 \]
\[ F = 9.19 \quad p < 0.01 \]
\[ F = 0.35 \quad p = 0.70 \]

Figure 3. Examples of confidence ellipses obtained for one representative participant from each group. $y$ is the vertical axis and $x$ is the horizontal axis of the participant’s sagittal plane. Ellipses obtained for the two delays (a) 0 s and (b) 8 s, for one CB participant (left), one LB participant (centre), and one BS participant (right).
types of distribution orientation for the two delays, which tended to be distributed along movement direction. The orientation of the pointing distribution in the late-blind participants is neither aligned with movement direction nor orthogonal to it, but rather in between the two types of distributions, for both delays.

4.1 Constant errors

As shown in figure 4a (direction movement error, $\alpha$), blind groups overshoot targets in direction, whereas the blindfolded-sighted group undershoots them. In spite of an overall delay effect showing that at 0 s delay pointing(s) overshoot with respect to pointing(s) at the 8 s delay, this effect is significant only for the blindfolded-sighted group.

Indeed, movement direction errors were affected by the group main effect ($F_{1,26} = 8.86, p < 0.005$) and also by the delay main effect ($F_{1,26} = 9.19, p < 0.01$); there was no evidence of a group × delay interaction ($F_{2,26} = 0.35, p = 0.70$).

Planned comparisons revealed that the magnitude of $\alpha$ was not significantly different in the congenitally blind group between the 0 and the 8 s delays ($F_{1,26} = 2.55, p = 0.12$), nor was it in the late-blind group ($F_{1,26} = 2.07, p = 0.16$). However, the difference was significant for the blindfolded-sighted group ($F_{1,26} = 4.72, p < 0.05$). There was further evidence that for the 0 s delay, congenitally blind and late-blind means did not differ ($F_{1,26} = 0.22, p = 0.64$), whereas both congenitally blind and late-blind groups differed from the blindfolded-sighted groups (CB versus BS: $F_{1,26} = 14.41, p < 0.001$; and LB versus BS: $F_{1,26} = 15.49, p < 0.001$). Finally, for the 8 s delay, the same pattern of results was found: mean values of $\alpha$ for the congenitally blind and late-blind did not differ ($F_{1,26} = 0.12, p = 0.72$), whereas both congenitally blind and late-blind groups differed from the blindfolded-sighted group (CB versus BS: $F_{1,26} = 12.32, p < 0.01$; LB versus BS: $F_{1,26} = 12.78, p < 0.01$).

Figure 4b (amplitude movement error, $R_0$) shows that the blind groups overshoot targets in amplitude, and the blindfolded-sighted group undershoots them. In spite of an overall delay effect showing that, at 0 s delay, pointings overshoot with respect

![Figure 4.](image)
to pointings at the 8 s delay, this effect is significant only for the late-blind and the blindfolded-sighted groups. 

\( R_0 \) was indeed affected by the group main effect \( (F_{1,26} = 23.38, p < 0.0001) \) and by the delay main effect \( (F_{1,26} = 17.81, p < 0.001) \). No interaction was observed \( (F_{2,26} = 0.79, p = 0.46) \).

Planned comparisons revealed that the magnitude of \( R_0 \) was only marginally significantly different for the congenitally blind group between the 0 and the 8 s delays \( (F_{1,26} = 3.41, p = 0.07) \). However, both delays differed in the late-blind and blindfolded-sighted groups (LB: \( F_{1,26} = 9.72, p < 0.01 \); BS: \( F_{1,26} = 5.37, p < 0.05 \)). It was further found that for the 0 s delay congenitally blind and late-blind means did not differ \( (F_{1,26} = 1.21, p = 0.27) \), whereas both congenitally blind and late-blind groups differed from the blindfolded-sighted group (CB versus BS: \( F_{1,26} = 31.72, p < 0.0001 \); LB versus BS: \( F_{1,26} = 38.30, p < 0.0001 \)). Lastly for the 8 s delay congenitally blind and late-blind values did not differ \( (F_{1,26} = 0.35, p = 0.55) \), whereas both congenitally blind and late-blind groups differed from the blindfolded-sighted group (CB versus BS: \( F_{1,26} = 35.97, p < 0.0001 \); LB versus BS: \( F_{1,26} = 37.10, p < 0.0001 \)).

4.2 Absolute error

Absolute distance error, \( d \), means were lower for both the congenitally blind and late-blind groups—which do not differ from each other—than for the blindfolded-sighted group, both delays being combined (as they do not differ). Indeed, as observed in figure 5a, the difference between the two delays was far from reaching statistical significance \( (F_{1,26} = 1.04, p = 0.31) \). Moreover, ANOVA confirmed table 1 observations: \( d \) was affected by group \( (F_{2,26} = 8.08, p < 0.01) \). No interaction was observed \( (F_{1,26} = 0.19, p = 0.82) \).

4.3 Variable errors

As expected, the surface area \( (s) \) is larger for the 8 s delay than for the 0 s delay. Indeed, the overall pointing variability (ellipse surface area) (figure 5b) tends to be
affected by the delay factor in all groups: larger pointing scatters are obtained in the three groups for the 8 s delay, than for the immediate response. Visual experience does not seem to affect ellipse surface areas, and this is especially clear in the longer-delay condition.

These qualitative observations are confirmed by statistical analysis. The main delay factor affected performance (\(F_{1,26} = 18.19\), \(p < 0.001\)), whereas no group effect was found (\(F_{2,26} = 0.28\), \(p = 0.75\)). No delay \(\times\) group interaction was observed (\(F_{2,26} = 0.54\), \(p = 0.58\)). Planned comparisons revealed that the delay effect was significant for each group (CB: \(F_{1,26} = 4.58\), \(p < 0.05\); LB: \(F_{1,26} = 5.42\), \(p < 0.05\); BS: \(F_{1,26} = 8.21\), \(p < 0.01\)).

Major-to-minor axis length ratio, \(r\), values listed in table 1 show a limited range of variation of this parameter: ellipses are similarly elongated, irrespective of the delay and the group. ANOVA confirmed this observation: the ellipse elongation was not affected by the main delay factor (\(F_{1,26} = 0.01\), \(p = 0.90\)), nor by the main group factor (\(F_{2,26} = 0.26\), \(p = 0.76\)); no group \(\times\) delay interaction was found (\(F_{2,26} = 1.82\), \(p = 0.18\)).

The orientation of the ellipse main axis, \(\beta\), (figure 6) in the congenitally blind group for both delays, and in the blindfolded-sighted group of the 0 s delay, accounts for the values closest to 180° (ie the distribution is aligned with the direction of the pointing movement). In the blindfolded-sighted group, for the 8 s delay, values were closest to 90°, meaning that the main axis tends to be aligned with the arc-shaped target array. In the late-blind group, \(\beta\) is in-between for both delays. Finally, for the 8 s delay the mean for the congenitally blind is higher than that for the visually experienced groups.

An ANOVA performed on \(\beta\) values revealed that ellipse orientation was marginally affected by the group main effect (\(F_{2,26} = 2.94\), \(p < 0.07\)), and by the delay main effect (\(F_{1,26} = 2.93\), \(p = 0.09\)); however, a group \(\times\) delay interaction was significant (\(F_{2,26} = 5.94\), \(p < 0.01\)). Planned comparisons were performed to determine the origin of the interaction.

With the 0 s delay, all groups performed similarly (CB versus LB: \(F_{1,26} = 1.81\), \(p = 0.18\); LB versus BS: \(F_{1,26} = 1.93\), \(p = 0.17\); CB versus BS: \(F_{1,26} = 0.06\), \(p = 0.8\)).

With the 8 s delay, the mean of the ellipse orientation for the congenitally blind group was significantly higher than that for the late-blind and blindfolded-sighted groups (CB versus LB: \(F_{1,26} = 6.13\), \(p < 0.05\); CB versus BS: \(F_{1,26} = 12.93\), \(p < 0.005\)); the late-blind and the blindfolded-sighted groups performed similarly (\(F_{1,26} = 1.47\), \(p = 0.23\)).

No effect of the delay factor was evident for the two blind groups (CB: \(F_{1,26} = 1.33\), \(p = 0.25\); LB: \(F_{1,26} = 0.006\), \(p = 0.93\)). However, \(\beta\) increased with delay in the blindfolded-sighted group (\(F_{1,26} = 11.41\), \(p < 0.01\)).

![Figure 6. Mean orientation of the major axis, \(\beta\), observed in each group for the two delays. (Means and standard errors are shown.)](image)
5 Discussion
This study provides the broadest characterisation of non-visual pointing available in the literature for the blindfolded-sighted, late-blind, and congenitally blind individuals along the 2-D sagittal plane, for both short and long delays between memorisation and pointing.

The results show that early and late visual-deprivation effects are distinguished from transient visual-deprivation effects, as long-term deprivation leads to increased capabilities (absolute distance estimations), unaltered organisation (surface area and ellipse elongation), and altered organisation (amplitude and direction estimates, orientation of pointing distribution) of the spatial representation with proprioception. We also found that the effect of the delay was scattered across parameters and groups, but overall was more pronounced in the visually experienced groups. Predictions were thus confirmed, except that the surface area of pointing was not found to be larger for the blindfolded-sighted group than for the other two groups, and that an effect of the delay was not found for absolute distance errors (Rossetti et al 1996).

5.1 The role of visual experience
The effect of visual deprivation is confirmed here as not being consistent, as highlighted by Thinus-Blanc and Gaunet (1997): long-term deprivation seems to be the predicting factor for direction and amplitude errors and absolute distance errors. Both blind groups performed differently from blindfolded-sighted participants, being smaller in blind groups, but they did not differ from each other. The values were staggered overall for the orientation of the major axis according to the degree of visual deprivation, with a marked effect of early visual experience on the exocentric frame of reference. For ellipse surface area and elongation of the ellipses, no effect of visual experience was observed.

Interestingly, some distortions in movement and encoding of the target position occurred according to the visual status: movement direction and amplitude were overvalued with long-term visual deprivation and undervalued with transient visual deprivation (figure 4). Movement bias is thus dependent on long-term visual deprivation, rather than on early visual deprivation. The hypometry (underestimation) found in sighted participants performing in an open-loop condition (Prablanc et al 1979; Rossetti et al 1994b), and traditionally attributed to the lack of contextual information (Coello and Magne 2000; Coello et al 2003), has not been found in blind participants. Our blind subjects may have developed alternative strategies to compensate for their chronic lack of contextual information that consequently affects depth perception: it has been shown that, in a task of imagined pointing to the left or right side of objects at three distances, the congenitally blind—but not the blindfolded-sighted subjects—showed no decrease in pointing span with increased image distance, indicating disagreement with the law of perspective (Arditi et al 1988). A renewal of attention was recently put on the perspective question: Heller (2002, in press) showed that “congenitally blind people do not all show the spontaneous use of perspective in their drawings”, but “preliminary research suggests that they are able to understand the conventions involved in perspective depictions”. We can conclude that, in our experiment, movement calibration depends on the modality used in everyday life; this is in accordance with Millar’s (1994) assumptions, for whom visual experience is used to calibrate movement encoding. Overall, this effect of long-term visual deprivation concurs with a recent review by Bavelier and Neville (2002), which showed that plastic changes across behaviours vary as a function of timing and with the nature of changes in experience, and are less sensitive to early sensory deprivation than previously stated.

As expected, the main effect of visual status was not found for elongation and ellipse orientation. However, the interaction between the delay and group factors for
the latter parameter showed that after a 0 s delay all groups performed similarly, but after an 8 s delay, the mean elliptic orientation of the congenitally blind group was significantly higher than that of the late-blind and blindfolded-sighted groups. Interestingly, orientation of the elliptic main axis in the congenitally blind group for both delays, and in the blindfolded-sighted group for the 0 s delay moves away from 90°, ie is aligned with the pointing movement direction; in the blindfolded-sighted group for the 8 s delay it moves closer to 90°, ie is aligned with the target arc-array; in the late-blind group the orientation is not aligned with movement direction nor is orthogonal to it. Moreover, the ratios were consistently around 2, suggesting that pointing distributions were elongated. We thus found a clear anisotropic distortion of memorised targets in which sensorimotor transformation leads to distorted spatial representations: the pointing distributions of the congenitally blind group rely on an egocentric frame of reference for both delays; that of the blindfolded-sighted group relies on an egocentric frame of reference for the shorter delay, but on an exocentric frame of reference for the longer delay; late-blind pointing distributions being in-between, for both delays. These findings are in conformity with our hypothesis stated in section 3 (Millar 1994; Rossetti et al 1996; Thinus-Blanc and Gaunet 1997): early visual deprivation has prevented the cognitive integration of an overall spatial arrangement of target locations, ie the use of an exocentric frame of reference. The difference between visually experienced and congenitally blind participants that appears after a delay strongly suggests that among adults early visual experience facilitates memorisation and representation of proprioceptive spatial information. This effect could be interpreted as structural differences in the visuo-spatial scratch pad—a subsystem of working memory assumed to store spatial information—in congenitally blind and blindfolded-sighted participants. Indeed, it has been shown earlier (Cornoldi et al 1991; Vecchi 1998) that the congenitally blind encounter working memory difficulties in processing spatial information such as the simultaneous management of large quantities of information. The distribution of the pointing of late-blind participants suggests that this group has taken advantage of early visual experience by exhibiting the use of an exocentric frame of reference (Millar 1994, pages 142–153), although the experience of living without vision has affected their frames of reference. This effect has been found previously for large-scale environment (Thinus-Blanc and Gaunet 1997). Proximal and locomotor spatial representations therefore share some properties (for the blind population, see Gaunet and Thinus-Blanc 1996; Gaunet et al 1997; Thinus-Blanc and Gaunet 1997; for the sighted population, see Andersen and Buneo 2002; Desmurget et al 1998; Paillard 1987, 1991; Thinus-Blanc and Gaunet 1997).

Absolute distance error values are considerably affected by the extra number of subjects, as compared to Rossetti et al (1996). This may be due to the fact that d is affected by constant and variable factors. Absolute distance errors are smaller for both blind groups—which do not differ (≈50.5 mm)—than for the blindfolded-sighted group (≈104.5 mm), with both delays pooled together. Long-term visual deprivation, rather than early visual experience, predicts the estimate of pointing accuracy. Thus, extended experience with a missing modality enables better performance than limited experience. This indicates that people tend to benefit perceptually from their everyday life experience. This adaptive behaviour may be driven by the attempt to reach further and higher in order not to miss and to hedge against high obstacles.

The last finding is that restricting spatial experience to senses other than vision does not allow a more consistent representation of the target location (ellipse surface area), with long-term experience of proprioception.

The outcome is thus that the different aspects of movement encoding are not similarly affected by visual experience, and therefore both modal and amodal processes are involved in the spatial representation of pointing at targets.
5.2 The dissociation of spatial representation according to delay

The dissociation effect is not consistent across parameters; however, because it was found more often overall in late-blind and blindfolded-sighted participants, one can conclude that the dissociation depends more on early than on late visual experience.

As expected (Rossetti et al 1996), an overall overshooting effect is observed for the shorter delay, both for direction and amplitude encoding: more specifically, pointings are increasingly overshot with the 0 s delay as compared with the 8 s delay, by the blindfolded-sighted group for direction encoding, and by the late-blind and blindfolded-sighted groups for amplitude encoding. The overestimation of movement amplitude and direction observed with the shorter delay seems to be a function of visual experience. Overall, after a delay the origin of the coordinate system becomes closer to the participant and lower in terms of gravity. It seems as if delay compresses space in terms of depth and gravity; one could speculate that the internal space model integrates the fact that a memorised target would be closer and lower in space with time, thereby following the inertial and gravity laws of a mobile target, respectively. In addition, the fact that the delay effect was more pronounced in the visually experienced participants suggests that the two frames of reference are more dependent on early visual than on non-visual experience. Moreover, an overall overshooting effect (accounting for smaller errors since the values are negative) is observed for the shorter delay as compared with the longer delay, both for direction and amplitude encoding. This effect is in agreement with many studies. Delay-dependent effects were found in recent memory location studies with sighted participants: Chieffi and Allport (1997) reported a significant increase in both absolute movement direction and amplitude errors, when adults pointed in the dark toward remembered locations after delays of 4, 10, and 30 s (for related findings, see Chieffi et al 1999). Similarly, Elliott and Madalena (1987) found an increase in movement amplitude error across delays of 2, 5, and 10 s. Bias with delay has not been shown to be related to the use of either frame of reference.

For $\beta$, there was no effect of the delay factor for the two combined blind groups. However, in the blindfolded-sighted group $\beta$ was modified by the delay, showing reliance on an exocentric frame of reference in early and late visual experience. Data replicate and therefore reinforce earlier evidence showing dissociation of immediate versus delayed spatial representation during somaesthetic modality processing (Rossetti 1998; Rossetti et al 1994b, 1996; Rossetti and Pisella 2002; Zuidhoek et al 2003). As expected, after a delay endpoint distribution becomes contingent upon the target array, whereas it becomes contingent upon movement encoding direction when pointings are performed as immediate responses. These effects have also been found when participants looked at a fixation point above an unseen pointing device (Bridgeman 1991, 2000; Rossetti 1998; Rossetti and Pisella 2002). The only other experiment comparable to the present one is the study by Helms-Tillery et al (1995). However, our findings are in conflict with theirs and a different experimental setting may account for the discrepancy (see Rossetti et al 1996 for discussion). Thus, our data confirm that two different information-processing systems are involved: one acts only in the immediate stimulus-driven movement, and another one takes over after a delay (Goodale et al 1994; Milner and Goodale 1993; Rossetti et al 1996).
Additionally, and unexpectedly, absolute distance errors are not affected by the delay. Although \( d \) effects can be explained in part by similar trends observed for constant errors (\( R_0 \), \( x \)), because constant-error analyses show delay effects, and the analysis of \( d \) does not, one can see how a performance index limits or may even bias the comprehension of underlying mechanisms. These observations confirm that subtle means (qualitative variables, such as constant variables, and the ratio of the lengths of the ellipse axes, and orientation of the main axis) must be used to investigate the role of sensory modalities in spatial representations (Thinus-Blanc and Gaunet 1997). Bias with delay has not been related to the use of either frames of reference.

Lastly, the surface is larger with the 8 s than with the 0 s delay, for all three groups. This confirms an obvious hypothesis: a delay between memorisation and output impairs the concentration of the pointing distribution. This observation is thus a general phenomenon, independent of any previous sensory experience.

Overall, it is finally worth noting that the dissociation found during both proprioceptive and visual processing (Bridgeman 1991, 2000; Rossetti 1998; Rossetti et al 1994b; Rossetti and Pisella 2002) suggests that this dissociation (egocentric versus exocentric encoding process) effect is supported by an amodal process, ie one independent of the sensory modality involved.

### 5.3 General conclusions

The factual conclusion of this study is that the effects of visual status and delay between memorisation and recall differ depending on the pointing parameters explored. Frames of reference used for performing spatial tasks do not therefore explain the discrepancies observed in earlier studies, and do not provide a general framework accounting for the role of visual experience in spatial representation properties. Unexpectedly, however, this study provides another illustration of the discrepant effects of visual deprivation on spatial behaviour, and thus of the complexity of the mechanisms underlying spatial representation.

Three facts taken together suggest that we must question or rule out the notion of a critical period associated with a definite effect of early sensory deprivation on spatial behaviour: (i) spatial representations involved during visual and proprioceptive pointing are similar (suggesting the involvement of an amodal representation); (ii) the different aspects of movement encoding are not similarly affected by visual experience (suggesting that both amodal and modal representations are involved, with, in the latter case, the effect of early and late visual experience); and (iii) overall, the dissociation effect occurs more often in visually experienced participants than in congenitally blind participants, but not for all parameters. This suggests modal representation of early visual experience. It now seems, and this has recently been supported by various behavioural and brain studies (Bavelier and Neville 2002), that sensory deprivation leads both to increased capabilities and altered organisation of the spared modalities. Blindness is thus not a deficit but a ‘push’ into an alternative developmental pathway. Blindness results in the use of compensatory strategies that are bound to lead to specific patterns of errors, accuracies, and variability. Indeed, an active visuo-spatial memory task showed that sighted and late-blind subjects generated a mental image of the matrix and a simplification of this image and that the early-blind subjects encoded each pattern element by its location in an \((x, y)\) coordinate system without visual representation during debriefing; but, despite this, all groups performed similarly (Vanlierde and Wanet-Defalque 2004). All groups are thus able to perform a visuo-spatial imagery task although they use different strategies. The hypothesis that spatial behaviour originates from both intrinsic (onset, duration, and nature of visual deprivation) and extrinsic (education, stimulation during development, etc) individual characteristics cannot be ignored. Thus, some cognitive and brain systems exhibit the existence of a well-defined
sensitive period during development, and there are systems exhibiting a remarkable life-long learning ability. The nature of plastic changes is specific, and depends on the timing of the altered experience and on the particular brain systems that are modified (Kujala et al 2000). Accordingly, the dichotomous notion of modal versus amodal representation conceals the notion of processes involving cross-modal behavioural plasticity.

A critical perspective results in providing a framework for explaining the discrepancies found in studies on blindness, and further provides a model accounting for the role of visual experience in spatial processing. This model suggests, first, that the effect of the onset of late blindness has to be evaluated at different times according to ability: pointing, mental rotation, or oriented locomotion. Second, the delay between memorisation and recall has to be controlled. Third, not only quantitative parameters, but qualitative parameters and strategies should also be considered.

Acknowledgments. We wish to thank Laure Pisella, Miriam Ittyerah, Isabelle Mileville, Serge Portalier, and the reviewers for their thoughtful comments on this work; and Christian Urquizar for his efficient technical assistance. This work was supported by grants from Fondation pour la Recherche Médicale to Yves Rossetti, from Fédération des Aveugles de France to both authors, and from Direction Régionale des Études Techniques to Florence Gaunet. We also wish to thank the Institut Départemental des Aveugles, the school l’Arc en Ciel, the Cannes Blanches association, and the Centre d’Aide par le Travail in Marseille, Thierry Bergère (Université de Lyon I), and Bernard Larritte (Hôpital Neurologique de Lyon). We wish to extend our gratitude to the blind people who volunteered to participate in the experiment.

References


Arditi A, Holtzman D, Kosslyn S M, 1988 “Mental imagery and sensory experience in congenital blindness” Neuropsychologia 1 1 – 12, 26


Chieffi S, Allport D A, 1997 “Independent coding of target distance and direction in visuo-spatial working memory” Psychological Research 60 244 – 250

Chieffi S, Allport D A, Woodin M, 1999 “Hand-centered coding of target location in visuo-spatial working memory” Neuropsychologia 37 495 – 502


Heller M A, in press “Picture perception and spatial cognition in visually impaired people”, in Touch, Blindness, and Neuroscience Eds S Ballesteros, M A Heller (Hillsdale, NJ: Lawrence Erlbaum Associates)
Prablanc C, Echalier J F, Komilis E, Jeannerod M, 1979 “Optimal response of eye and hand motor systems in pointing at a visual target. I: Spatiotemporal characteristics of eye and hand movements and their relationships when varying the amount of visual information” Biological Cybernetics 35 113–124
Rossetti Y, Procyk E, 1997 “What memory is for action” Behavioral and Brain Sciences 20 34–36
Vecchi T, 1998 “Visuo-spatial imagery in congenitally totally blind people” Memory 6 91–102