Reference frame preferences in haptics differ for the blind and sighted in the horizontal but not in the vertical plane

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Abstract. We investigated which reference frames are preferred when matching spatial language to
the haptic domain. Sighted, low-vision, and blind participants were tested on a haptic-sentence-
verification task where participants had to haptically explore different configurations of a ball and a
shoe and judge the relation between them. Results from the spatial relation “above”, in the vertical
plane, showed that various reference frames are available after haptic inspection of a configuration.
Moreover, the pattern of results was similar for all three groups and resembled patterns found
for the sighted on visual sentence-verification tasks. In contrast, when judging the spatial relation
“in front”, in the horizontal plane, the blind showed a markedly different response pattern. The
sighted and low-vision participants did not show a clear preference for either the absolute/relative
or the intrinsic reference frame when these frames were dissociated. The blind, on the other
hand, showed a clear preference for the intrinsic reference frame. In the absence of a dominant
cue, such as gravity in the vertical plane, the blind might emphasise the functional relationship
between the objects owing to enhanced experience with haptic exploration of objects.

1 Introduction
When communicating about the spatial relations between objects, it is important to
use the same perspective. For example, while having tea you might be looking for the
sugar and you ask your companion. In response, you might receive the instruction:
“the sugar is in front of the teapot”. The exact location of the sugar could be different
according to your perspective, the perspective of your companion, or the perspective
of the teapot. In order to make this communication successful it is essential that you
and your companion compute the same reference frame.

Seminal work on understanding spatial descriptions has been done by Carlson
and colleagues (Carlson 1999; Carlson-Radvansky and Irwin 1994; Carlson-Radvansky and
Logan 1997; Logan 1994). When a spatial sentence describes a particular scene, verbal
and perceptual information have to be compared. This information is converted into a
spatial mental representation which allows comprehension of the situation (Tversky
1991) and requires several steps. The reference object (the teapot in the example above)
needs to be identified in order to impose the origin of a reference frame, yielding a
set of endpoints defining the searching space for the located object (the sugar in the
example above—Carlson 1999).

Reference frames consist of three axes, which parse up space into different direc-
tions specifying location, and have several parameters that can be adjusted: eg origin,
orientation, direction, and distance (Carlson and Van Deman 2004; Carlson-Radvansky
and Logan 1997). Reference frames are presumed to be independent from the coordi-
nate system used, eg Cartesian or polar, but refer to the distinctions between the
origins of coordinate systems (Levinson 1996). Generally, in spatial language processing
three reference frames are distinguished: (i) the environment, such as gravity, cardinal
directions, or prominent landmarks, (ii) the perceiver, or (iii) the perceived object. These
reference frames have been labeled absolute (A), relative (R), and intrinsic (I), respectively.
In a canonical situation, these three reference frames are aligned (ARI), for instance when the teapot for the foregoing example is facing you and your companion is sitting next to you at the same side of the table. However, when the teapot is rotated and no longer facing you, the intrinsic (I) reference frame is misaligned with the absolute and relative (AR) reference frame with regard to an “in front of” judgment.

Reference frames form a core aspect of spatial mental representations, which are of key importance to human cognition. Representing spatial location is essential for perception in order to localise objects and track them over time, eventually allowing efficient actions on stable and moving objects. Reference frames have played a central role in different lines of research. Studies on spatial language processing and reference frames have focused mainly on comparing sentences to visual scenes and refer to the definitions of reference frames mentioned above (Carlson 1999; Carlson and Van Deman 2008; Carlson-Radvansky and Jiang 1998). Another common distinction is between egocentric and allocentric reference frames. In egocentric reference frames objects are represented with respect to the body, hand, or head of the perceiver. In allocentric reference frames objects are represented with respect to the environment or prominent landmarks. In a non-linguistic visual mental-rotation task there was evidence of environmental or allocentric and retinal or egocentric references frames, which could be dissociated by tilting the head of the subject (McMullen and Jolicoeur 1990). Evidence from neglect patients showed a double dissociation between body-centred and stimulus-centred reference frames on visual figure discriminative-cancellation tasks (Ota et al 2001). In the haptic domain there is also evidence of different reference frames. For example, when subjects were asked to identify numbers or letters on their body, subjects reported mirror-reversed items on their forehead and normal on the back of their head, implying different perspectives (Corcoran 1977; Parsons and Shimojo 1987). Evidence of egocentric body-centred and hand-centred reference frames and allocentric reference frames was also found in haptic mental-rotation, matching, and parallel-setting tasks (Carpenter and Eisenberg 1978; Postma et al 2007, 2008; Prather and Sathian 2002; Volcic et al 2009).

Surprisingly little work has been done on how spatial language is matched to perception in the non-visual modalities. How would a particular spatial sentence match with a concurrent haptic inspection of a configuration? It has been suggested that the initial inputs can be either modal or linguistic, but both types of information eventually converge into a supramodal representation (Cattaneo and Vecchi 2008; Röder et al 2007; Struiksma et al 2009). The supramodal representation contains the basic spatial information, such as reference frames; however, a connection with the input modalities is maintained. A spatial representation can be accessed from perceptual or verbal input, yielding functional equivalence (Denis and Zimmer 1992; Loomis et al 2007; for a review see Struiksma et al 2009); nevertheless, because modal connections are maintained, subtle differences are possible. The functional equivalence might suggest that spatial information, for example reference frames, is also available through haptic input. The aim of the current study was to investigate which reference frames are preferred when matching spatial language to the haptic domain. A group of individuals that is of particular interest here are the visually impaired. Blind people no longer have, or never have had, experience with the visual domain. Instead, they rely on hearing and touch to obtain information about the world. On the other hand, low-vision people still have some access to visual input, but might not be able to use it to its full extent, and thus turn to rely on the other sensory modalities. The behaviour and preferences of these groups could give insight in the relevance and the quality of visual input for reference frame use based on haptic input. In the current study we tested sighted, low-vision, and blind participants on a haptic sentence-verification task where participants had to judge the relation between a ball and a shoe after haptic exploration.
Previous research on reference frames in the blind has suggested that congenitally blind people rely on egocentric encoding, since proprioceptive, vestibular, touch, and movement information is available with a body-centred or hand-centred reference (Millar 1994; Röder et al 2007) and more distal information is reduced and more difficult to process (for reviews, see Cattaneo et al 2008; Thinus-Blanc and Gaunet 1997). The egocentric reference frame can also be associated with the relative reference frame explained above (Levinson 1996). As such, we might expect that blind participants in our haptic sentence-verification task are more inclined to use the relative reference frames than sighted participants. Alternatively, since haptic object handling and search is quite common in blind individuals, a preference for the non-egocentric intrinsic reference frame might be observed. Heller and Kennedy (1990) have shown that, in a tactile Piagetian three-mountain task, blind subjects were able to adopt a non-egocentric perspective, similar to blindfolded sighted controls. Postma et al (2007) reported on a haptic matching task. Subjects had to haptically match shapes to cut-outs in a board and later describe the configuration of the shapes. They found that blind individuals used more object-related spatial-language (ie intrinsic reference frame) terms than sighted persons, whereas the latter produced slightly more board references (ie absolute reference frame) when describing the layout of a previously inspected object array.

Preference differences between the reference frames can be observed especially in situations where the reference frames are dissociated. We explored this for two different spatial relations. According to the spatial framework model from Franklin and Tversky (1990) the vertical axis with spatial terms “above/below”, aligned with gravity, is the predominant axis, followed by “in front/back”, which has a perceptual and functional asymmetry, and then “left/right”. Previous research in the visual domain has primarily used “above” in the vertical plane (Carlson 1999; Carlson and Logan 2001; Logan 1995; Logan and Compton 1996); therefore, we first tested this spatial relation. In order to stress the different reference frames we also tested “in front”, which is in the horizontal plane. This latter relation is more ambiguous and can be influenced by motion. For example, in a stationary situation “in front” refers to the object closest to an observer; however, when moving, “in front” refers to the object farthest away (Alloway et al 2006). The increased ambiguity might stress the intrinsic reference frame, making it a more plausible response option. This expectation is based on research with visual paradigms. We speculate that blind people would not show such a switch of interpretation since they rely more on haptic input, even during movement. Hence, “in front” might be more stable and refer to the object closest to the experiencer. In the current study we investigated whether blind participants rely to a larger extent on the absolute/relative reference frame, similar to the “above” situation, while the sighted participants rely to a larger extent on the intrinsic reference frame, compared to the “above” situation. In addition, the results on the low-vision participants might indicate whether the availability of vision, albeit impaired, yields results comparable to blind or sighted preferences. In other words, does the quality of vision determine performance, or is the access to visual information the most important factor.

2 Methods
2.1 Participants
Participants all were visitors of a Dutch annual event for low-vision and blind individuals, from two consecutive years. The first group of participants consisted of 343 visitors: 154 sighted controls (SC), 146 low-vision (LV), and 43 blind (BL) participants; for details, see table 1. Participants were asked about their visual status. The blind participants declared that they have no residual vision, or at most light/dark perception. The low-vision participants reported residual vision between 1% and 60%. Owing to the setup of the study, there was a trade-off between testing a large number of participants
and acquiring detailed etiology. Finding a large sample of blind participants is a challenge; therefore, we have chosen to test as many people as possible while, unfortunately, sacrificing a more detailed etiology.

A Kruskal–Wallis test revealed a significant group difference in terms of age: \( \chi^2_{2,343} = 13.18, p = 0.001 \). An a-posteriori test using Mann–Whitney pairwise comparisons with Bonferroni correction (\( z_B = \sqrt{2}/3 = 0.017 \)) showed that the low-vision participants were significantly older than the sighted (\( U = 8738.00, N_1 = 146, N_2 = 154, p = 0.001, \) two-tailed) and the blind (\( U = 2214.00, N_1 = 146, N_2 = 43, p = 0.003, \) two-tailed). The blind and sighted did not differ from each other in age (\( U = 2987.50, N_1 = 43, N_2 = 154, p = 0.328, \) two-tailed). There was also a significant group difference in education level: \( \chi^2_{2,343} = 13.18, p = 0.001 \). Pairwise comparisons revealed that the sighted controls had a higher education level than the low-vision participants (\( U = 8689.00, N_1 = 154, N_2 = 146, \) \( p < 0.001, \) two-tailed), but there was no difference with the blind group (\( U = 2811.00, N_1 = 154, N_2 = 43, p = 0.105, \) two-tailed) or between the low-vision and the blind participants (\( U = 2911.00, N_1 = 146, N_2 = 43, p = 0.445, \) two-tailed). The number of males was lower in the sighted group than in the other two (\( \chi^2_{2,343} = 8.288, p = 0.016 \)).

The second group of participants consisted of 403 visitors: 170 sighted controls (SC), 181 low-vision (LV), and 52 blind (BL) participants (for details, see table 1). Again, there was a significant difference in age (\( \chi^2_{2,403} = 21.50, p < 0.001 \)). The low-vision participants were significantly older than the sighted controls (\( U = 12766.00, N_1 = 181, N_2 = 170, \) \( p = 0.006, \) two-tailed), who were significantly older than the blind (\( U = 3293.50, N_1 = 170, N_2 = 52, p = 0.005, \) two-tailed). As in the first group, there was a significant difference in education level (\( \chi^2_{2,403} = 23.10, p < 0.001 \)). The sighted controls had a significantly higher education level than the low-vision participants (\( U = 11153.50, N_1 = 170, N_2 = 181, p < 0.001, \) two-tailed), but there was no significant difference with the blind group (\( U = 4060.00, N_1 = 170, N_2 = 52, p = 0.343, \) two-tailed). Also, as in the first group the number of males was lower in the sighted group than in the other two (\( \chi^2_{2,403} = 7.188, p = 0.027 \)).

### 2.2 Stimulus material
The stimulus set consisted of a small-size baby shoe (±13 cm) and a small ball (±4 cm diameter), the distance between them was approximately 4 cm. The stimuli were placed in boxes (33 cm × 33 cm × 33 cm), which were covered with fabric and placed on one side on a table adjacent to each other. All boxes contained identical shoes and balls. In the centre of the fabric on the side facing the participants an incision was made; this incision was kept small in order to prevent sighted subjects from looking into the boxes. As a result, participants could place one hand inside the box to feel the stimuli. The stimuli were close enough together in order to feel the ball and a part of the shoe simultaneously. For the “above” judgments, the shoe and ball were attached to the

### Table 1. Descriptives for all groups for both experiments (SC = sighted controls, LV = low-vision, BL = blind).

<table>
<thead>
<tr>
<th>Group</th>
<th>N</th>
<th>Male/%</th>
<th>Age/years ± SD</th>
<th>Education/code ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Group 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC</td>
<td>154</td>
<td>36.36</td>
<td>47.70 ± 13.23</td>
<td>5.77 ± 0.79</td>
</tr>
<tr>
<td>LV</td>
<td>146</td>
<td>51.37</td>
<td>54.14 ± 17.32</td>
<td>5.37 ± 1.00</td>
</tr>
<tr>
<td>BL</td>
<td>43</td>
<td>53.49</td>
<td>45.12 ± 15.38</td>
<td>5.53 ± 0.96</td>
</tr>
<tr>
<td>Group 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SC</td>
<td>170</td>
<td>35.29</td>
<td>50.76 ± 14.92</td>
<td>5.71 ± 0.87</td>
</tr>
<tr>
<td>LV</td>
<td>181</td>
<td>45.86</td>
<td>55.30 ± 16.49</td>
<td>5.21 ± 1.05</td>
</tr>
<tr>
<td>BL</td>
<td>52</td>
<td>53.85</td>
<td>44.12 ± 15.51</td>
<td>5.50 ± 1.06</td>
</tr>
</tbody>
</table>
far-end vertical plane. For the “in front” judgments, the shoe and ball were attached
to the bottom of the box. There were different conditions based on the orientation
of the shoe and the position of the ball: five conditions for “above” and seven for
“in front”. When all reference frames were aligned, the shoe was in the canonical
orientation. In the case of “above” this meant that the shoe was placed with the
sole to the ground and the nose to the left or right (cARI, cNo). In order to disso-
ciate the reference frames the shoe was rotated 90° along the z-axis with the nose
pointing upwards yielding non-canonical orientations (ncAR, ncI, ncNo, see figure 1).

``absolute/relative “yes”``

``intrinsic “yes”``

Figure 1. Example of positions of the ball that corre-
spond to an absolute/relative and intrinsic “yes” response
to “above”.

Table 2. Example of stimuli and stimulus codes.

<table>
<thead>
<tr>
<th>Stimulus Orientation</th>
<th>Reference frame describing “yes”</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>“above”</td>
<td>canonical</td>
<td>cARI</td>
</tr>
<tr>
<td></td>
<td>absolute/relative/intrinsic</td>
<td></td>
</tr>
<tr>
<td>“in front”</td>
<td>canonical</td>
<td>cNo</td>
</tr>
<tr>
<td></td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>“above”</td>
<td>canonical</td>
<td>cAR</td>
</tr>
<tr>
<td></td>
<td>absolute/relative</td>
<td></td>
</tr>
<tr>
<td>“in front”</td>
<td>canonical</td>
<td>cI</td>
</tr>
<tr>
<td></td>
<td>intrinsic</td>
<td></td>
</tr>
<tr>
<td>“above”</td>
<td>non-canonical</td>
<td>ncAR</td>
</tr>
<tr>
<td></td>
<td>absolute/relative</td>
<td></td>
</tr>
<tr>
<td>“in front”</td>
<td>non-canonical</td>
<td>ncI</td>
</tr>
<tr>
<td></td>
<td>intrinsic</td>
<td></td>
</tr>
<tr>
<td>“above”</td>
<td>non-canonical</td>
<td>ncNo</td>
</tr>
<tr>
<td></td>
<td>none</td>
<td></td>
</tr>
</tbody>
</table>
In this critical case a “yes” response implies the use of a different reference frame than for a “no” response. For example, in figure 1, depending on the location of the ball, a “yes” response to the question “Is the ball above the shoe?” indicates the use of the absolute/relative\(^{(1)}\) or intrinsic reference frame.

In the case of “in front” the canonical orientation of the shoe was the sole to the ground and the nose pointing towards the subject (cARI, cNo). However, a 180° rotation along the y-axis yielded a situation where the nose was pointing away from the subject resulting in dissociation of the reference frames. We have labeled these cases canonical, since they highly resemble the true canonical orientation (cAR, cI). Another ambiguous situation was created by a 90° rotation along the y-axis. The nose was now pointing to the left or right and the reference frames were again dissociated. These cases have been labeled non-canonical (ncAR, ncI), see table 2 for an overview of all stimuli.

3 Design and procedure
Visitors to the stand were asked to place one hand inside the box. They were told that each box contained a small shoe and a ball. Their instruction was to feel both stimuli and to judge whether the sentence “The ball is X the shoe” was true, X could be “above” or “in front of” (the Dutch version is “Is de bal boven/voor de schoen?”). Participants responded by saying: “yes” or “no”.\(^{(2)}\) For each subject the responses were noted. There were five trials in the “above” version and seven trials in the “in front” version. The order of the boxes was randomised and changed every 10 participants to avoid order effects. After the participants had finished the trials, they were asked to give a few descriptives: gender, age, and information about their visual capabilities and education.

3.1 Data analysis
The responses were recoded “no” = 0, or “yes” = 1. The same codes were used for both experiments. The response consistency in the ambiguous trials was computed by calculating the number of switches (0,1 for “above”; 0,1,2 for “in front”) Since the number of participants was unequal for the three groups and the level of measurement was nominal, non-parametric statistics were appropriate. The main effects of proportion of “yes” responses between different conditions were computed by the McNemar test using a binomial distribution. The between-group effects per condition were analysed by means of an exact significance test for Pearson’s \(\chi^2\). The exact significance test was selected because there were cells that had an expected count less than 5, which violated the assumption for the regular \(\chi^2\) test. The group effects were further analysed by means of pairwise comparisons with the exact significance test for Pearson’s \(\chi^2\). The significance level was corrected for multiple comparisons with the Bonferroni method.

4 Results
4.1 “Above”
The proportion of “yes” responses for all three groups on the five different conditions in the vertical plane are given in figure 2. In the cARI condition, when all reference frames aligned and the ball was placed above the shoe, almost all participants responded “yes”.

\(^{(1)}\)In Dutch and other European languages the relative reference frame is preferred (Levinson 1996). However, the participants stood in front of a table which was the prominent landmark and dictated the orientation of the absolute reference frame. In that situation the absolute and relative reference frames were aligned. To be precise we will refer to the absolute/relative reference frame, since it cannot be determined whether the absolute reference frame was irrelevant to participants.

\(^{(2)}\)Participants were all visitors of an annual event for the visually impaired. In a laboratory setting it would have been beneficial to allow participants to rate the description on a graded scale. Since many people participated at the event we have chosen to use only two response alternatives to simplify instructions.
When the shoe was in the same orientation, but the ball was placed at the heel of the shoe (cNo) most participants responded “no”. When the shoe was rotated 90° to the right in a non-canonical orientation and the ball was placed next to the sole (ncNo) almost all participants responded “no”. The conditions of interest were those where the shoe was rotated and the ball was placed above the shoe according to the subject’s point of view (ncAR), or according to the shoe’s point of view (ncI). In order to verify whether participants had access to multiple reference frames, the McNemar test was used to compare cARI with ncAR and ncI with ncNo. In the ncAR condition participants mostly responded with “yes”, although significantly fewer than in the cARI condition (\(N = 343\), exact \(p = 0.001\)). In the ncI condition, participants were more inclined to respond with “no”, although a significant amount of participants responded with “yes”, as indicated by the significant difference from the ncNo condition (\(N = 343\), exact \(p = 0.001\)). See figure 2 for an illustration of these effects.

The conditions of interest were further analysed for group differences by means of an exact significance test for Pearson’s \(\chi^2\). In the ncAR condition there were no group differences (\(\chi^2_{2,343} = 0.590\), exact \(p = 0.742\)); however, in the ncI condition there were significant group differences (\(\chi^2_{2,343} = 7.047\), exact \(p = 0.029\)). The group differences were further tested with pairwise comparisons, the significance level was corrected for multiple comparisons with the Bonferroni method (\(\alpha_B = \alpha/3 = 0.017\)). The pairwise comparisons revealed a significant difference between sighted and low-vision participants. Low-vision participants were more inclined to respond with “no” (\(\chi^2_{1,300} = 6.412\), exact \(p = 0.013\)). There was no significant difference between sighted and blind participants (\(\chi^2_{1,197} = 0.001\), exact \(p = 1.000\)), and low-vision and blind participants (\(\chi^2_{1,189} = 3.421\), exact \(p = 0.098\)).

The majority of participants were very consistent in their response pattern (84.8%). This means that if they responded according to the relative reference frame on ncAR, they also responded according to the relative reference frame on ncI and, similarly, for the intrinsic reference frame. This pattern did not differ between the different subgroups that were tested using the same order of the trials (\(\chi^2_{40,343} = 49.691\), exact \(p = 0.131\)). Together these results show a highly similar pattern for all three groups and replicate previous results from visual paradigms.
4.2 “In front”

The proportions of “yes” responses for all three groups on the seven different conditions in the horizontal plane are given in figure 3. In the canonical condition (cARI) when the ball was placed in front of the shoe and a “yes” response was required, almost all participants responded with “yes”. In the canonical situation where a “no” response was required (cNo) most participants also responded with “no”. The same pattern is true for the non-canonical “no” condition (ncNo). The differences arise when the reference frames are in conflict. In order to verify whether participants had access to multiple reference frames, the McNemar test was used to compare cARI with ncAR and cAR, and ncNo with ncI and cI. In the canonical and non-canonical absolute/relative conditions (cAR and ncAR) the proportion of “yes” responses was significantly lower than in the cARI condition in which all reference frames were aligned ($N = 403$, exact $p < 0.001$).

In the canonical and non-canonical intrinsic conditions (cI and ncI), the proportion of “yes” responses was significantly higher than in the ncNo condition ($N = 403$, exact $p < 0.001$). See figure 3 for an illustration of these effects.

The conditions of interest were further analysed by means of an exact significance test for Pearson’s $\chi^2$. The group differences were further tested with pairwise comparisons, the significance level was corrected for multiple comparisons with the Bonferroni method ($a = 0.017$). When the absolute/relative frames dictated a “yes” response, in both canonical and non-canonical orientations of the shoe, there were group differences (see table 3 for details, row cAR and ncAR). Approximately half of the sighted and low-vision participants gave a “yes” response, whereas the blind participants were

### Table 3.

Statistics for the results of “in front”. Columns represent the main effect and pairwise comparisons between different groups [sighted controls (SC), low-vision (LV), and blind (BL)]. Rows represent different conditions: cAR = canonical absolute/relative, ncAR = non-canonical absolute/relative, cI = canonical intrinsic, ncI = non-canonical intrinsic.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Main effect</th>
<th>SC versus LV</th>
<th>SC versus BL</th>
<th>LV versus BL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\chi^2$</td>
<td>$\chi^2$</td>
<td>$\chi^2$</td>
<td>$\chi^2$</td>
</tr>
<tr>
<td></td>
<td>$\text{exact } p$</td>
<td>$\text{exact } p$</td>
<td>$\text{exact } p$</td>
<td>$\text{exact } p$</td>
</tr>
<tr>
<td>cAR</td>
<td>18.084</td>
<td>&lt; 0.001</td>
<td>1.269</td>
<td>0.286</td>
</tr>
<tr>
<td>ncAR</td>
<td>19.798</td>
<td>&lt; 0.001</td>
<td>2.065</td>
<td>0.166</td>
</tr>
<tr>
<td>cI</td>
<td>12.515</td>
<td>0.002</td>
<td>1.662</td>
<td>0.200</td>
</tr>
<tr>
<td>ncI</td>
<td>10.499</td>
<td>0.005</td>
<td>7.128</td>
<td>0.010</td>
</tr>
</tbody>
</table>

![Figure 3. Results for “in front” for sighted controls (SC), low-vision (LV), and blind (BL) participants (±1 SEM).](image-url)
significantly more inclined to respond with “no” (see figure 3 and table 3 for details). In the canonical situation where the *intrinsic* frame dictated the “yes” response (cI) the proportion of “yes” responses in the blind was significantly higher than in the sighted and low-vision participants (see table 3, row cI). In the non-canonical *intrinsic* situation (ncI) the proportion of “yes” responses was significantly higher for the blind and sighted than for the low-vision participants. In the low-vision group, approximately half of the participants responded with “yes”, similar to the canonical *absolute/relative* situation (see figure 3 and table 3 row ncI for details). The results for the blind are clearly different from those of the sighted and visually impaired. Blind participants seem to favour the use of the *intrinsic* reference frame, while sighted and low-vision participants show no clear preference for the *intrinsic* or the *absolute/relative* reference frames.

Again the majority of participants were consistent in their response pattern (71.5%). This means that, if they responded according to the *relative* reference frame on ncAR, they also responded according to the *relative* reference frame on cAR, ncI, and cI, and similarly for the *intrinsic* reference frame. The other participants (23.8%) responded to the same reference frame in three out of four of the ambiguous cases. Only a small number of participants (4.7%) responded according to both the *absolute* (2 cases) and the *intrinsic* (2 cases) reference frames. This pattern did not differ between the different subgroups that were tested with the same order of the trials ($\chi^2_{88,403} = 76.803$, exact $p = 0.797$).

### 4.3 “Above” versus “in front”

The studies on “above” and “in front” both tested the non-canonical conditions of interest, where either the *absolute/relative* or the *intrinsic* reference frames dictated the “yes” response (ncAR and ncI respectively). This enabled us to compare the two groups on each condition with an exact significance test for Pearson’s $\chi^2$. All groups showed a significant decrease in the proportion of *absolute/relative* responses, and consequently an increase in *intrinsic* responses for “in front” in comparison with “above” (see table 4 for details of the statistics). This pattern was expected for the sighted and low-vision participants. Surprisingly, the blind participants also showed an increase of *intrinsic* responses, as was also demonstrated by the results from “in front” alone.

#### Table 4. Statistics for the results of comparing “above” to “in front” for the sighted controls (SC), low-vision (LV), and blind (BL) participants. Rows represent different conditions: ncAR = non-canonical *absolute/relative*, ncI = non-canonical *intrinsic*.

<table>
<thead>
<tr>
<th>Condition</th>
<th>SC $\chi^2$</th>
<th>exact $p$</th>
<th>LV $\chi^2$</th>
<th>exact $p$</th>
<th>BL $\chi^2$</th>
<th>exact $p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ncAR</td>
<td>61.140</td>
<td>&lt;0.001</td>
<td>50.946</td>
<td>&lt;0.001</td>
<td>45.012</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>ncI</td>
<td>42.123</td>
<td>&lt;0.001</td>
<td>41.016</td>
<td>&lt;0.001</td>
<td>16.408</td>
<td>&lt;0.001</td>
</tr>
</tbody>
</table>

### 5 Discussion

The main goal of the current study was to explore which reference frames are preferred when matching a spatial description to a haptic inspection of a configuration. Specific interest focused on whether people with no or limited visual input show different preferences than sighted controls. Notably, the results from the current experiment clearly showed that various reference frames are available under these circumstances.

The results on “above”, in the vertical plane, are in line with previous results found in the visual domain with sighted participants (Carlson 1999; Carlson-Radvansky and Irwin 1993, 1994). In a rating study Carlson-Radvansky and Irwin (1993, 1994) found...
a clear preference for the *absolute/relative* reference frames, but there was a significant difference between the canonical condition in which all reference frames were aligned and the non-canonical condition in which the *absolute/relative* reference frames dictated a “yes” response. This indicated that participants did not resolve to use an *absolute/relative* strategy, using only those reference frames while ignoring the *intrinsic* reference frame. The induced conflict between the reference frames in the non-canonical *absolute/relative* reference frame condition resulted in a significant drop in acceptance rate which indicated that the *intrinsic* reference frame had been available and was subsequently discarded. Further proof refuting the *absolute/relative* strategy came from the difference between the non-canonical *intrinsic* reference frame condition and the non-canonical No condition, where none of the reference frames dictated a “yes” response. If participants had used such a strategy then there should have been no difference saying “no” to the non-canonical *intrinsic* and non-canonical No. Instead Carlson-Radvansky and Irwin (1993, 1994) found that participants accepted non-canonical *intrinsic* significantly more often than non-canonical No. The availability of the *intrinsic* reference frame followed by a rejection results in a higher cognitive load compared to a situation where only the *absolute/relative* reference frames were available. This higher cognitive load is reflected in the response times also reported by Carlson-Radvansky and Irwin (1994). They found that participants were slower in rejecting a non-canonical *intrinsic* than a non-canonical No. The present results from our haptic sentence-verification task are in line with these effects. The fact that the acceptability of the non-canonical No was significantly lower than that of the non-canonical *intrinsic* condition indicates that the *intrinsic* reference frame had been available, although it was not the preferred reference frame.

Interestingly, the low-vision and even the blind participants showed the same behaviour as the sighted participants, i.e. a clear preference for the *absolute/relative* reference frame, but also the availability of the *intrinsic* reference frame. Only in the non-canonical *intrinsic* condition a difference between the three groups emerged. In this situation the low-vision participants were more inclined to respond with “no” indicating an even stronger preference for the *absolute/relative* reference frame than the sighted and the blind. The idea that blind subjects were more inclined to use the *relative* reference frame is not supported by these results. Alternatively, it is also not the case that sighted subjects are more inclined to use the *relative* reference frame. Instead, the behaviour of blind and sighted is highly similar. The low-vision participants showed a slightly stronger preference for the *relative* reference frame in the non-canonical *intrinsic* condition. However, this difference was only marginally significant when compared to the sighted participants and did not differ from the blind participants. Therefore, this minor effect in the low-vision group should not be overemphasised. A limitation of the present study was the absence of detailed information on the etiology of the blind and low-vision participants. As such, to parametrically determine the effect of the amount of residual vision was outside of the scope of this study; however, this would be interesting for a follow-up study.

With the second spatial relation “in front”, in the horizontal plane, apparent differences between the groups emerged. The low-vision and the sighted participants generally showed the same behaviour, while the response pattern from the blind was clearly different. The responses in the control conditions in which all reference frames were aligned and indicated either a “yes” or a “no” response were the same for all three groups. This suggests that participants understood the task they were doing. A closer analysis of the conditions of interest in which there was a conflict between the *absolute/relative* and *intrinsic* reference frames revealed that for the sighted the clear preference for *absolute/relative* had diminished in comparison to the findings in the vertical plane. On average, approximately 50% of the participants responded according to the *absolute/relative* reference frames and approximately 50% according to the *intrinsic* reference frame, while this was approximately 90% and 10%, respectively, in the vertical plane.
As mentioned before, the spatial relation “in front” is more ambiguous as demonstrated by the influence of movement on the interpretation of the relation (Alloway et al 2006; Miller and Johnson-Laird 1976). As predicted, this was also demonstrated by the current results, where half of the participants have used the intrinsic reference frame. A similar pattern was also found for the visually impaired, implying that the availability of vision has a strong influence on judging the spatial relation.

In contrast, the results from the blind participants showed a markedly different pattern. We hypothesised that, for the blind, haptic input during movement would provide a more stable interpretation for “in front” according to the absolute/relative reference frames. This would have been reflected by a stronger preference for the absolute/relative reference frames in the blind. Contrary to our expectations blind participants seemed to prefer the intrinsic reference frame. Instead of using their body-centred coordinate system which would have yielded a bias in favour of the absolute-relative reference frames, blind participants focused on the reference object, in this case the shoe. Evidently the orientation of the shoe was of greater relevance to the blind than to the sighted and visually impaired. We conjecture that the increased experience with haptic object handling in the blind is crucial here. Touch is their primary source of input for information about the world around them and determining the orientation of objects as such is extremely helpful. Directly feeling whether you pick up a shoe by its nose or its heel when you want to put it on offers a great benefit. In line with this idea, various researchers have pointed out that situational context and functional relation between objects also strongly determine which reference frame is most dominant (Carlson and Kenny 2006; Carlson-Radvansky et al 1999; Carlson-Radvansky and Radvansky 1996; Coventry and Garrod 2004). The functional relation focuses attention on one of the objects, favouring the intrinsic reference frame. On the other hand, the relative reference frame is associated with the relation between the object and the viewer (Carlson-Radvansky and Radvansky 1996; Miller and Johnson-Laird 1976). The results of Carlson-Radvansky and Radvansky (1996) corroborate this distinction and showed that the choice of the reference frame used to describe a scene was influenced by the presence of a functional relation. For example, in a picture with a mail carrier and a mailbox participants preferred the intrinsic reference frame when the mail carrier was facing the mailbox, as if he was posting a letter. When the mail carrier was facing the opposite direction the functional relation disappeared and participants preferred the relative reference frame.

In the case of our task where participants had to judge whether or not the “ball was in front of the shoe” there was also a clear functional relationship. When the ball was positioned in line with the front of the shoe, one could imagine kicking the ball away. According to this functional relationship we would then expect participants to prefer the intrinsic reference frame in the canonical condition where all frames overlap, the canonical intrinsic condition and the non-canonical intrinsic condition. In accordance with judging the functional relationship, using the intrinsic reference frame in the other conditions predicts “no” responses for the canonical absolute/relative and non-canonical absolute/relative conditions. This is exactly what we have found for the blind participants for judgments in the horizontal plane. Not only the orientation of the shoe was more important to the blind, but especially the functional relation between the ball and the shoe predicts the pattern of results.

The functional explanation of the results for the horizontal plane does not only apply to the blind, but could equally well hold for the sighted and low-vision participants. There is clear evidence of more ambiguity when the spatial relation “in front” needs to be verified, as demonstrated by the larger proportion of intrinsic responses in all groups. This pattern fits with the spatial framework model proposed by Franklin and Tversky (1990); Franklin and Tversky argue that the above/below axis is most
strongly anchored, based on a functional constancy in combination with gravity, followed by the front/back axis, which has a functional and perceptual asymmetry, and, last, by the left/right axis, which is symmetric. The current results show that the judgments of “above” were very stable, while the judgments of “in front” showed more variety. Moreover, Franklin and Tversky showed that, when observers were reclining, the ordering of the axes changed. Since the above/below axis no longer coincided with gravity, the vertical axis lost its special status. The asymmetries of the bodily axis predicted that the front/back axis was most accessible, followed by the above/below, and then the left/right axis. These different orderings, based on the position of the observer, indicate that the spatial framework model is adaptable. The relevance of specific external and internal features, such as gravity and bodily axis, can change. In the case of “above”, gravity was dominant and predicted the use of the relative reference frame. However, for “in front”, subjects could rely on a bodily asymmetry, yielding a relative response; on the other hand, movement induced ambiguity, increasing the stability of the intrinsic reference frame, or a functional asymmetry would yield an intrinsic response. Sighted and low-vision subjects showed no clear preference for one reference frame, while the blind were more inclined to use the intrinsic reference frame.

We have discussed two possible mechanisms that might explain this increase of intrinsic responses: movement-induced ambiguity and the functional relation between objects. With the current experiment it is not possible to completely disentangle the influence of these two mechanisms and we, of course, leave open the possibility that yet other mechanisms might explain the preference of the blind for an intrinsic response. However, we think that the most likely explanation lies in the latter. Results from the blind seem to follow a pattern that fits more with the functional explanation. They show a clear preference for the intrinsic reference frame with a “yes” response when the ball was in front of the nose of the shoe and a “no” response in the other conditions. We speculate that the results from the sighted and low-vision participants are mainly due to the movement-induced ambiguity, since in all conditions of interest the proportion of intrinsic responses was approximately around 50% and no clear preference for the functional relation was observed. Alternatively, they could have been relying on the functional relationship between the ball and the shoe, but to a lesser extent than the blind. In order to fully understand the contribution of the functional relationship between objects further research is needed where the functional relationship is manipulated. If we are correct about the idea that the blind were relying stronger on the functional relationship than the sighted, then in the absence of a functional relationship we would predict that the blind would prefer the absolute/relative reference frames, since in the haptic domain movement would not induce ambiguity leaving the interpretation of the absolute/relative reference frame stable; ie the object closest to you would still be considered “in front”. On the other hand, in the sighted and low-vision groups we would expect similar results as found for “in front”. In line with evidence from the visual domain, the movement-induced ambiguity would increase the reliability of the intrinsic reference frame.

In conclusion, the present study has shown that various reference frames are available in sighted, low-vision, and blind participants during haptic spatial sentence-verification. These results provide supporting evidence for a supramodal representation of spatial information (Cattaneo and Vecchi 2008; Röder et al 2007; Struiksma et al 2009) where reference frames are available for comparison between spatial language and visual, but also haptic situations. Moreover, for judging “above”, in the vertical plane, gravity seems to play a dominant role, as demonstrated by the relatively few occasions of using the intrinsic reference frame when it was dissociated from the absolute/relative reference frame. This was true for all three groups, including the blind participants.
On the other hand, for the spatial relation “in front”, in the horizontal plane, a different pattern was found. For the sighted and low-vision group, owing to the absence of a strong cue such as gravity, the intrinsic sides of the reference object became an important cue. This became clear from the increased number of intrinsic reference frame responses in the cases where the reference frames were dissociated. Most notable, the blind participants showed an even stronger intrinsic reference frame preference in this situation. The emphasis on the functional relation between the ball and the shoe may explain this outcome. Evidently, blind participants might rely stronger on the details of the reference and located object, which could be due to their enhanced experience with haptic exploration of objects.

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