On the use of visual information in infant reaching actions
van Wermeskerken, M.M.

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Chapter 5

Reaching for moving objects is affected by background motion in 6- to 10-month-old infants

Manuscript in preparation:
Abstract

It is suggested that in human adults the use of visual information for action mode selection and movement control is dissociated (Milner & Goodale, 1995, 2008). More specifically, action mode selection primarily relies upon allocentric information, whereas movement control mainly exploits egocentric information. In the present study it is investigated whether this dissociation is already present in 6- to 10-month-old infants; that is, whether usage of allocentric information is limited to action mode selection (i.e., reaching with one or the other hand) or is also exploited for movement control (i.e., reaching kinematics). Infants were presented with laterally approaching objects at two speeds (i.e., 20 and 40 cm/s) against a stationary or moving background. Background motion affects allocentric information about the object’s velocity relative to its background. Results indicated that object speed in relation to infants’ action capabilities constrained both infants’ action mode selection and movement control. Background motion also affected action mode selection, albeit that the effects of object speed were more pronounced. Importantly, background motion did not affect movement control, except for movement onset. These findings indicate that information usage is not completely dissociated for action mode selection and movement control during early development, although alternative interpretations cannot be ruled out.
Introduction

Research in adults suggests a division in the human visual system into two functionally dissociated and neuro-anatomically separate visual systems: *vision for movement* and *vision for perception* (Goodale & Milner, 1992, 2004b; Milner & Goodale, 1995, 2008). The vision for movement system is engaged in the online control of movements whereas vision for perception is involved in the perception of objects, events, and situations. Apart from engaging separate cortical areas (i.e., the dorsal and ventral stream, respectively), these systems can be distinguished on a behavioral level by the type of visual information that they preferably exploit (Haffenden & Goodale, 2000; Michaels, 2000; Milner & Goodale, 2008; van der Kamp, Oudejans, & Savelsbergh, 2003). That is, vision for movement mainly, but not exclusively, relies on egocentric (i.e., context-independent) sources of information, whereas vision for perception primarily exploits allocentric (i.e., context-dependent or relative metrics) sources of information. This dissociation in information usage becomes evident in the differential effects that visual illusions have on visual perception and movement control (e.g., Aglioti, DeSouza, & Goodale, 1995; Bruno, Bernardis, & Gentilucci, 2008; Ganel, Tanzer, & Goodale, 2008), although controversy exists (e.g., Franz, Hesse, & Kollath, 2009; Schenk & McIntosh, 2010; Smeets & Brenner, 2006). For instance, the perception of the properties of a shaft (e.g., its length) embedded in the Müller-Lyer illusion is clearly affected by the object’s visual surroundings (i.e., the tails of the illusion), which underlines that vision for perception uses context-dependent, allocentric information. Yet, when the object is grasped, the unfolding of hand aperture is scaled to the physical size of the object and remains relatively immune to the illusion, demonstrating that vision for movement is primarily reliant upon context-independent, egocentric information (Aglioti et al., 1995; Ganel et al., 2008; Milner & Goodale, 2008; Otto-de Haart, Carey, & Milne, 1999; van Doorn, van der Kamp, & Savelsbergh, 2007). Importantly, it has recently been suggested that vision for perception also contributes to the selection of an appropriate mode for action (van Doorn et al., 2007; Milner & Goodale, 2008). That is, the selection of using one or two hands to grasp relatively

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1 Note that, originally, the “vision for movement” system was termed “vision for action” (Goodale & Milner, 1992). Yet, it is our contention that the term “movement” more directly speaks to the function of the dorsal stream, which yields the control of movements and does not include action mode selection (van Doorn et al., 2007). In addition, it should be noted that the current study only includes behavioral data and does not validate activations in the ventral or dorsal stream. Hence, findings are interpreted within the two-visual systems model on a behavioral level (i.e., exploitation of visual information) and are only suggestive with respect to the underlying neuronal circuitry.
large shafts embedded in the Müller-Lyer illusion involved, like the perception of their length, the use of the contextual, allocentric information, suggesting contributions of vision for perception.

Thus far, it has remained unclear to what degree this dissociation in information usage for action mode selection and movement control, and hence between the two visual systems, is already present in early infancy. However, previous work did demonstrate that action mode selection and movement control are likely to be dissociated from 5 months of age onwards (van Wermeskerken, van der Kamp, & Savelsbergh, 2011a). That is, although infants of this age were able to select adaptive reaching modes (i.e., one- or two-handed reaching) and adjusted their movement kinematics (i.e., the unfolding of bimanual hand aperture) to the size of the object, it was found that these processes were not mutually constraining. Selection of a reaching mode that is appropriate for the size of the object, thus, did not necessarily go together with the control of an infant's reaching movements being adjusted to object size, and vice versa. Yet, although consistent with such a hypothesis, it was not directly assessed whether action mode selection and movement control relied upon different sources of visual information as predicted by the two-visual systems model.

The present study therefore aims to examine whether in infants aged 6 to 10 months the usage of allocentric (or context-dependent) information is limited to action mode selection, as would be predicted based on observations in adults, or is also exploited for movement control. Habituation and preference looking methods have indeed demonstrated that infants are able to use allocentric information in perceiving objects and events (for an overview see van Wermeskerken, van der Kamp, & Savelsbergh, 2010). For instance, one-month-old infants exploit relative velocity information (i.e., stimulus motion relative to static boundaries of a monitor) although this ability initially seems to be restricted to large velocity differences (i.e., differences in relative velocity of 9 °/s), with smaller detectable differences in velocity with increasing age (i.e., up to 1.2 °/s at 4.5 months of age; Aslin & Shea, 1990; Bertenthal & Bradbury, 1992; Dannemiller & Freedland, 1989). However, whether this information can also be used to guide action mode selection, and perhaps affects movement control as well, has not been investigated so far. Hence, in the present study, 6- to 10-month-old infants were presented with laterally approaching objects that moved at two speeds (20 and 40 cm/s) against a background that was stationary or either moved in the same direction as the object or moved in the opposite direction. The background motion
yields manipulation of allocentric sources of information, since it changes the velocity of the object relative to its background (see e.g., Smeets & Brenner, 1995); yet, the background motion does not influence the egocentric information sources that specify the velocity of the object relative to the infant.

Thus far, previous studies on infants’ reaching for moving objects has shown that time constraints (i.e., object speed) in relation to the infants’ action capabilities affect both infants’ action mode selection and control of reaching (e.g., van Hof, van der Kamp, & Savelsbergh, 2008; von Hofsten, 1983). That is, increasing the speed of the object, results in smaller time-windows within which the interception can be made successfully. Accordingly, research examining infants’ movement kinematics have shown that higher time constraints result in higher peak velocities and shorter movement durations (Out, Savelsbergh, & van Soest, 2001; von Hofsten, 1983). With respect to action mode selection, van Hof and colleagues demonstrated that infants are more inclined to reach with the hand contralateral to the side from which the object approaches, that is, the right hand, when the object approaches from the left. In other words, infants tend to use the contralateral hand when time constraints are high as compared to low time constraints (van Hof, van der Kamp, Caljouw, & Savelsbergh, 2005). Yet, in these studies only the speed of the object relative to the infant was manipulated; information about object speed relative to the background was not manipulated. By introducing background motion, this study examines whether infants use this allocentric information source to guide action mode selection (i.e., reaching with the hand ipsi- or contralateral to the side from which the object approaches) and/or the subsequent reaching movements. Based upon the two-visual systems model, we hypothesized that if infants’ use of visual information is functionally dissociated for action mode selection and movement control, then background motion would primarily affect infants’ reaching modes, and hence, have no effects (or only reduced effects) on movement control.

**Methods**

**Participants**

Eleven 6-month-old ($M = 6.0$ months, $SD = .15$ months), fifteen 8-month-old ($M = 8.0$ months, $SD = .14$ months) and ten 10-month-old ($M = 10.0$ months, $SD = .24$ months) healthy full-term infants participated in the study after their parents gave
written informed consent. 25 additional infants (12 6-month-olds, 6 8-month-olds, and 7 10-month-olds) were tested but excluded from the analysis because of fussing, crying, not reaching or technical failure. The experiment was approved by the local institution’s ethical committee.

**Apparatus and Task**

Infants were seated in an infant chair with adjustable head and trunk supports such that the infants had their trunk straight, head upright, and limbs free to move. The seat was reclined at 18° from the vertical and was positioned in front of a conveyor belt, which was 300 cm long, 6.5 cm wide, and 80 cm high. Objects were attached by the use of a magnet to a holder placed on the conveyor belt. All objects afforded one-handed grasping and consisted of polystyrene, multicolor balls (diameter of 4 cm) or small animal puppets of similar size. The height of the holder as well as sagittal (object-infant) distance could be adjusted such that the object moved within arm reach of the infant. The conveyor belt was set in motion by a Galil DMC-700 motion controller, such that the object approached the infant from the left at speeds of 20 or 40 cm/s. Behind the conveyor belt a large screen (140 cm x 106 cm) was positioned on which a background was projected using a projector (ASK Proxima C250, China; for a schematic representation of the set-up see Figure 5.1). The background was black with randomly oriented white stripes and was either stationary or moved. In case of a moving background, it moved in the direction opposite to the object (i.e., right to left, resulting in an increase of relative velocity) or in the same direction as the object (i.e., left to right, resulting in a decrease of relative velocity) but 10 cm/s slower than the object. That is, in case of an object velocity of 20 cm/s, the background moved with 10 cm/s; for an object velocity of 40 cm/s, it moved with 30 cm/s. The infant chair was positioned to the right of the center of the screen, to ensure that infants had enough time to intercept the object.

\[2\] In a pilot experiment these conditions were found to effectively affect adults’ (n=6) perception of (relative) object velocity. That is, adults were presented with two events after which they had to verbally judge the velocity of the second object relative to the first object (i.e., ‘slower’, ‘faster’). The first event consisted of an object that moved laterally with 40 cm/s. The background was either stationary or continuously moved in the same or opposite direction with 30 cm/s. In the second event, an object moved laterally with a velocity varying between 30 and 50 cm/s with intervals of 5 cm/s. The background remained stationary. In line with previous observations (Smeets & Brenner, 1995), the findings showed that if the background moved in the opposite direction, adults perceived the object as moving faster than if the background was stationary. On the contrary, if the background moved in the same direction, the perceived velocity of the object was lower as compared to when the background was stationary.
Infants’ reaching movements were recorded with a high-speed camera (Basler A602f, Basler AG, Ahrensburg, Germany) that sampled at 100Hz. A 3-D motion analysis system (Optotrak 3020, Northern Digital Inc., Waterloo, Ontario, Canada) recorded infants’ reaching movements with a sampling frequency of 200 Hz. Two pre-calibrated Optotrak camera units were positioned at 2.5 m from the infant on either side of the experimental setting. The infants wore bracelets with three infrared light-emitting diodes (IREDs) on each wrist to assure that the entire movement could be tracked. An additional IRED was attached to the holder to track the movement of the object. High-speed recordings and the Optotrak system were synchronized by the use of an external trigger, which also controlled object and background motions.

**Design and Procedure**

Once the infant was seated in the chair, the experimenter adjusted the height of the holder and the distance between the infant and the object. The infant was allowed to grasp and play with the toy, while the experimenter fastened the bracelets with the IREDs to the infant’s wrists. The experiment started after moving the support to the left of the screen and triggering all devices.

During the first up to a maximum of three trials, the object approached the infant from the left with 10 cm/s to familiarize the infant with the experimental set-up. During these trials the background was stationary. Thereafter, the speed of the object was set at 20 cm/s for nine trials in which each background condition (stationary, same, and opposite direction) was presented three times in random order. Subsequently, object speed was 40 cm/s for nine trials, presenting each background condition three times in random order. Then, infants were presented with blocks of three trials in which each background condition was presented once. Infants were alternately presented with a block in which object speed was 20 cm/s and 40 cm/s (the background conditions were...
adjusted accordingly). The experiment was terminated when the infant consistently refused to reach, got fuzzed or cried. The experiment lasted about 30 minutes on average.

**Data analysis**

*Reaching mode.* Reaching mode was scored using the reaching kinematics (see below) in combination with the video recordings. A reach was defined as an arm movement directed towards the object and approaching it within a fist-size distance. For each trial it was scored whether the infant reached and if so, whether this reach was left-, right- or two-handed. For each infant and each of six object velocity by background conditions the mean percentage of reaches over all trials was computed. Subsequently, the mean percentage of bimanual reaches over all reaches and the mean percentage of left-handed reaches over all unimanual reaches were computed. These percentages were then entered into Generalised Estimated Equations (GEE) models. GEE is equivalent to regression analysis but accounts for repeated observations within participants. Also, since missing values do not result in excluding the participant (e.g., some infants did not perform left- or right-handed reaches in all conditions), the number of included participants can be maximized. GEE analyses were conducted using SPSS 16.0 with the correlation structure set to exchangeable.

First, we explored the effects of object velocity on infants’ reaching modes (i.e., reaching percentage, percentage of bimanual reaches, and percentage of left-handed reaches) by including object velocity, age, and the interaction between these variables in the model. Velocity was entered as categorical variable, which enabled us to directly test the difference between the two velocity conditions. Age was entered as covariate. Only data for the stationary background condition was included.

In a second step, we analyzed the effects of background condition within each velocity condition. Background, age, and the interaction between the two variables were included in the model. Background was entered as categorical variable with the same direction condition as reference category (i.e., testing the difference between (1) same and stationary and (2) same and opposite background conditions).

*Reaching kinematics.* The 3-D positions of the recorded Optotruk IREDs were filtered with a second-order recursive Butterworth low-pass filter with a cutoff frequency of 10 Hz. For the reaching movements, data of one of the three IREDs with most data across trials were selected for analysis. A least squares method for
interpolation was used if the missing data did not exceed 100 ms. Otherwise the reach was excluded from further analysis. Subsequently, initiation and end of the reaching movement was determined using the multiple sources of information method (Schot, Brenner, & Smeets, 2010). This method entails that several objective functions together compute the likeliness that a certain instant is the onset or end of a movement. The moment with the highest likelihood is considered to reflect movement onset or end. These moments were then compared to the video recordings and in the case that these moments were clearly too late or too early, the moments were adjusted accordingly.

Subsequently, infants’ reaching kinematics were analyzed. To enhance the number of reaches, we divided the bimanual reach into a left-handed and right-handed reach and collapsed them with the unimanual left- and right-handed reaches, respectively. For each reach we computed (1) movement duration (ms), (2) peak velocity (cm/s), (3) relative moment of peak velocity (%), (4) average velocity (cm/s), (5) object distance relative to body midline at reach initiation (cm), (6) time to contact relative to body midline at reach initiation (s), (7) distance between hand and body midline at reaching end (cm), and (8) the number of movement units. A movement unit was defined as an acceleration and a deceleration phase which lasted at least 100 ms, yielded a maximum velocity of at least 10 cm/s, and in which the difference between both velocity minima and the velocity maximum exceeded 2 cm/s (Thelen, Corbetta, & Spencer, 1996; von Hofsten, 1991; von Hofsten & Rönnqvist, 1993). For each infant and each of six conditions, averages of these kinematic variables were computed for right-handed and left-handed reaches separately. We then explored which of these variables were constrained by the velocity manipulation (i.e., comparing the 20 cm/s and 40 cm/s object velocity conditions with a stationary background) and then assessed for these variables the effects of background condition within each velocity condition. This was done separately for right- and left-handed reaches. In order to be able to include each of seven kinematic variables in one analysis, a repeated measures MANOVA was conducted (rather than GEE analysis; because bimanual reaches were included in both the left- and right-handed reaches, the number of infants that were excluded due to insufficient data was minimized) with object velocity (20, 40 cm/s) as within-subject

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3 The risk of this method is that bimanual reaches have more weight as compared to the unimanual reaches, since they are split into two unimanual components and, hence, contribute twice to the outcome. An alternative method would be to eliminate all bimanual reaches or to only include one of the two unimanual components. However, to enhance the number of reaches included in the analyses (and to minimize the number of empty cells), we chose to include both unimanual components.
factor and age (6, 8, 10 months) as between-subjects factor. The variables that were significantly affected by object velocity were subsequently submitted to a repeated measures MANOVA with background (similar directed, stationary, opposite directed) as within-subject factor and age (6, 8, 10 months) as between-subjects factor. The dependent variables were distributed normally and had equal variances. Hyun-Feldt adjustments of the p values were reported in cases that the sphericity assumption was violated (i.e., epsilon’s > 1.0). All post hoc comparisons were conducted with no adjustments (LSD; \( p < .05 \)).

**Table 5.1** Number (and percentages) of trials, reaches, and contacts for each age group.

<table>
<thead>
<tr>
<th>Age</th>
<th>Trials</th>
<th>Reaches</th>
<th>Contacts</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 months (n=11)</td>
<td>30.5 ± 5.1</td>
<td>28.5 ± 5.1 (93.3%)</td>
<td>22.3 ± 5.3 (78.0%)</td>
</tr>
<tr>
<td>8 months (n=15)</td>
<td>32.7 ± 3.7</td>
<td>30.3 ± 6.4 (91.8%)</td>
<td>22.8 ± 8.5 (73.1%)</td>
</tr>
<tr>
<td>10 months (n=10)</td>
<td>33.7 ± 7.5</td>
<td>31.3 ± 6.4 (93.4%)</td>
<td>24.1 ± 6.3 (77.6%)</td>
</tr>
</tbody>
</table>

**Results**

The 36 infants received a total of 1163 trials during which 1080 (92.8%) reaches were performed that resulted 828 times (76.7%) in contact with the object. As can be seen in Table 1, infants performed reaches equally often and were equally successful in contacting the object, irrespective of age (One-Way ANOVA’s; \( p > .1 \)).

**Reaching modes**

To explore the effects of object velocity and background manipulations on infants’ reaching behaviors, separate GEE’s were conducted on the percentages of reaches, bimanual reaches, and left-handed reaches, respectively.

We first explored the effects of object velocity on infants’ reaching behavior by including only the conditions with a stationary background in the model (see Figure 5.2). This did not reveal any age effects for the percentage of reaches (see Table 5.2, Eq. 1.1 – 1.3). However, object velocity clearly constrained the percentages of bimanual and left-handed reaches. That is, with higher velocities, infants were less inclined to reach bimanually (Eq. 1.2, Table 5.2) and with their left hand (Eq. 1.3, Table 5.2). Put differently, with higher object velocities, infants were more inclined to reach with their right hand (i.e., the reaching mode that provides most time to intercept the object).

We then analyzed the effects of background for each velocity condition separately.
Results

Chapter 5

Figure 5.2 Mean percentages of reaches, bimanual reaches, and left-handed reaches for each age group and each velocity and background condition. Error bars represent standard error of the mean.

Table 5.2 Results of the GEE regression analyses by which the percentage of reaches, bimanual reaches, and left-handed reaches was predicted as function of object velocity (i.e., stationary background).

<table>
<thead>
<tr>
<th>Eq.</th>
<th>% Reach</th>
<th>Coefficient</th>
<th>Lower 95% CI</th>
<th>Upper 95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>% Reach</td>
<td>Constant</td>
<td>92.91</td>
<td>77.45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Velocity</td>
<td>-3.42</td>
<td>-30.02</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Age</td>
<td>0.27</td>
<td>-1.61</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Velocity x Age</td>
<td>0.16</td>
<td>-3.19</td>
</tr>
<tr>
<td>1.2</td>
<td>% Bimanual</td>
<td>Constant</td>
<td>84.48</td>
<td>47.92</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Velocity</td>
<td>-11.16</td>
<td>-21.71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Age</td>
<td>-2.98</td>
<td>-7.43</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Velocity x Age</td>
<td>5.31</td>
<td>-2.62</td>
</tr>
<tr>
<td>1.3</td>
<td>% Left</td>
<td>Constant</td>
<td>39.92</td>
<td>-11.33</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Velocity</td>
<td>-44.99</td>
<td>-60.87</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Age</td>
<td>3.24</td>
<td>-2.70</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Velocity x Age</td>
<td>-0.39</td>
<td>-9.46</td>
</tr>
</tbody>
</table>
For the 20 cm/s velocity condition it was revealed that the percentage of reaches differed between the condition with the background moving in the same direction as the object and the stationary background condition, with fewer reaches being performed in the latter condition (Eq. 2.1, Table 5.3). Yet, an interaction effect between Age and Background condition (i.e., Similar – Stationary) indicates that this effect was different for each age group. Indeed, only the 6-month-olds showed a decline in reaching attempts in the stationary as compared to the similar moving background condition. By contrast, the 8-month-olds reached equally often and the 10-month-olds reached more often in the stationary background condition. In addition, an age effect indicated that fewer bimanual attempts were performed with increasing age (Eq. 2.2, Table 5.3). No effects were revealed for the percentage of left-handed attempts.

For the 40 cm/s velocity condition, it was revealed that the percentage of reaches

Table 5.3 Results of the GEE regression analyses by which the percentage of reaches, bimanual reaches, and left-handed reaches was predicted as function of background for the 20 cm/s object velocity conditions.

<table>
<thead>
<tr>
<th>Eq.</th>
<th>Coefficient</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Lower</td>
</tr>
<tr>
<td>2.1</td>
<td>% Reach</td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>107.46</td>
<td>92.97</td>
</tr>
<tr>
<td>Similar – Stationary</td>
<td>-14.56</td>
<td>-26.80</td>
</tr>
<tr>
<td>Similar – Opposite</td>
<td>-2.20</td>
<td>-21.20</td>
</tr>
<tr>
<td>Age</td>
<td>-1.55</td>
<td>-3.36</td>
</tr>
<tr>
<td>Age x Similar – Stationary</td>
<td>1.82</td>
<td>0.35</td>
</tr>
<tr>
<td>Age x Similar – Opposite</td>
<td>0.15</td>
<td>-2.13</td>
</tr>
<tr>
<td>2.2</td>
<td>% Bimanual</td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>105.96</td>
<td>75.83</td>
</tr>
<tr>
<td>Similar – Stationary</td>
<td>0.87</td>
<td>-6.88</td>
</tr>
<tr>
<td>Similar – Opposite</td>
<td>-0.91</td>
<td>-9.67</td>
</tr>
<tr>
<td>Age</td>
<td>-5.80</td>
<td>-9.82</td>
</tr>
<tr>
<td>Age x Similar – Stationary</td>
<td>0.41</td>
<td>-5.15</td>
</tr>
<tr>
<td>Age x Similar – Opposite</td>
<td>0.35</td>
<td>-5.69</td>
</tr>
<tr>
<td>2.3</td>
<td>% Left</td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>58.65</td>
<td>-22.19</td>
</tr>
<tr>
<td>Similar – Stationary</td>
<td>-26.66</td>
<td>-86.30</td>
</tr>
<tr>
<td>Similar – Opposite</td>
<td>-24.23</td>
<td>-96.64</td>
</tr>
<tr>
<td>Age</td>
<td>-0.40</td>
<td>-10.23</td>
</tr>
<tr>
<td>Age x Similar – Stationary</td>
<td>4.46</td>
<td>-2.92</td>
</tr>
<tr>
<td>Age x Similar – Opposite</td>
<td>3.14</td>
<td>-5.18</td>
</tr>
</tbody>
</table>
increased with age (Eq. 3.1, Table 5.4). In addition, fewer bimanual reaches (Eq. 3.2, Table 5.4) and more left-handed reaches (Eq. 3.3, Table 5.4) were performed with increasing age. Interestingly, background condition clearly affected infants’ reaching modes, the largest differences being between the two moving background conditions (right panel of Figure 5.2).

Overall, fewer bimanual attempts were performed when the background moved in opposite direction \( (p < .01) \) or remained stationary \( (p = .07) \) as compared to the condition during which the object and background moved in the same direction (Eq. 3.2). However, a significant interaction effect (i.e., Age x Background [Similar – Opposite]) indicated that this effect was limited to the 6-month-old infants; in the 8- and 10-month-olds this effect was not observed. In addition, background condition influenced the occurrence of left-handed reaches, but only between the moving

**Table 5.4** Results of the GEE regression analyses by which the percentage of reaches, bimanual reaches, and left-handed reaches was predicted as function of background for the 40 cm/s object velocity conditions.

<table>
<thead>
<tr>
<th>Eq.</th>
<th>95% CI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Coefficient</td>
</tr>
<tr>
<td>3.1 % Reach</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Similar – Stationary</td>
</tr>
<tr>
<td></td>
<td>Similar – Opposite</td>
</tr>
<tr>
<td></td>
<td>Age</td>
</tr>
<tr>
<td></td>
<td>Age x Similar – Stationary</td>
</tr>
<tr>
<td></td>
<td>Age x Similar – Opposite</td>
</tr>
<tr>
<td>3.2 % Bimanual</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Similar – Stationary</td>
</tr>
<tr>
<td></td>
<td>Similar – Opposite</td>
</tr>
<tr>
<td></td>
<td>Age</td>
</tr>
<tr>
<td></td>
<td>Age x Similar – Stationary</td>
</tr>
<tr>
<td></td>
<td>Age x Similar – Opposite</td>
</tr>
<tr>
<td>3.3 % Left</td>
<td>Constant</td>
</tr>
<tr>
<td></td>
<td>Similar – Stationary</td>
</tr>
<tr>
<td></td>
<td>Similar – Opposite</td>
</tr>
<tr>
<td></td>
<td>Age</td>
</tr>
<tr>
<td></td>
<td>Age x Similar – Stationary</td>
</tr>
<tr>
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<td>Age x Similar – Opposite</td>
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background conditions and this effect was different for each age group (Eq. 3.3). Whereas the 6-month-olds performed more left-handed reaches when the background moved in opposite direction, this effect was reversed by 10 months.

**Movement control**

Before exploring the effects of background movement on infants’ movement control, we first established the effects of object velocity on infants’ reaching kinematics against a stationary background. To this end, we performed separate multivariate analyses of variance for right- and left-handed reaches (i.e., bimanual reaches were split into left- and right-handed reaches) with all kinematic variables as dependent variables; object velocity (i.e., 20 and 40 cm/s) was included as within-subject factor
(i.e., repeated measure) and age as between-subjects factor. Subsequently, similar analyses were performed to assess additional effects of background motion, but including only those dependent variables that were affected by changes in object velocity.

**Effects of velocity manipulation**

*Right-handed reaches.* Infants who performed right-handed reaches in the 20 cm/s and 40 cm/s velocity conditions with stationary background were included in this analysis (n=34). The RM-MANOVA revealed a main effect of Velocity (Wilks Λ = .04, $F(8,24) = 79.9$, $p < .001$, $η^2_p = .96$) and Age (Wilks Λ = .25, $F(16,48) = 3.0$, $p < .01$, $η^2_p = .50$). Separate analyses of variance indicated that with higher object velocity (1) reach duration decreased ($F(1,31) = 48.8$, $p < .001$, $η^2_p = .61$; Figure 5.3a), (2) infants

![Figure 5.4](image)

**Figure 5.4** Representation of kinematical parameters of left-handed reaches that were affected by the velocity manipulation (i.e., stationary background); (a) reach duration, (b) average velocity, (c) number movement units, (d) relative moment of peak velocity, and (e) time to contact at reach initiation (ttc). *Error bars represent standard error.*
moved their hands faster (i.e., increase in average velocity; $F(1,31) = 6.3, p < .05, \eta_p^2 = .17$; Figure 5.3b), (3) performed fewer movement units ($F(1,31) = 6.4, p < .05, \eta_p^2 = .17$; Figure 5.3c), (4) displayed a shorter deceleration phase (i.e., later relative moment of peak velocity; $F(1,31) = 5.0, p < .05, \eta_p^2 = .14$; Figure 5.3d), and (5) initiated their reach at a larger object-body midline distance ($F(1,31) = 23.1, p < .001, \eta_p^2 = .43$; Figure 5.3e). In addition, with increasing age, relative moment of peak velocity occurred earlier (i.e., longer deceleration phase; $F(2,31) = 3.87, p < .05, \eta_p^2 = .20$, Figure 5.3d).

Mean velocity and peak velocity was higher amongst the 6-month-olds ($F(2,31) = 5.6, p < .01, \eta_p^2 = .26$ and $F(2,31) = 4.5, p < .05, \eta_p^2 = .23$, resp.; see Figures 5.3b and 5.3f) as compared to 8-month-olds (both $p$’s < .05).

**Left-handed reaches.** A total of 29 infants performed left-handed reaches in both the 20 cm/s and 40 cm/s velocity conditions with stationary background. A similar RM MANOVA as described above was conducted which revealed a main effect of Velocity ($\text{Wilks } \Lambda = .02, F(8,19) = 111.84, p < .001, \eta_p^2 = .98$). Separate univariate tests revealed that with an increase in object velocity, (1) reach duration decreased ($F(1,26) = 63.02, p < .001, \eta_p^2 = .71$, Fig 4a), (2) infants moved their hands faster (i.e., higher average velocities, $F(1,26) = 12.92, p < .01, \eta_p^2 = .33$, Figure 5.4b), reaches consisted of fewer movement units ($F(1,26) = 45.56, p < .001, \eta_p^2 = .64$, Figure 5.4c), relative moment of peak velocity occurred later (i.e., shorter deceleration phase, $F(1,26) = 19.62, p < .001, \eta_p^2 = .43$, Figure 5.4d), and (5) reaches were initiated at shorter times to contact ($F(1,26) = 111.02, p < .001, \eta_p^2 = .81$, Fig 5.4e). There were no age effects or interaction effects ($p$’s > .1).

Together these findings reveal that object velocity constrains infants’ reaching kinematics and does so differently for left- and right-handed reaches. Whereas some variables (i.e., reach duration, mean velocity, number of movement units, and relative moment of peak velocity) were similarly affected by an increase in velocity across hands, there were also variables that influenced one hand but not the other. For instance, right-handed reaches were initiated at different object distances from the body midline, whereas left-handed reaches were initiated at different times to contact relative to body midline. Finally, age-related effects in reaching kinematics were only observed for the right-handed reaches.

**Effects of background manipulation**

In order to explore the effects of background motion on infants’ reaching
observed for the right-handed reaches.

Finally, age-related effects in reaching kinematics were only

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kinematics and does so differently for left- and right-handed reaches. Whereas

20 cm/s and 40 cm/s velocity conditions with stationary background. A similar

compared to 8-month-olds (both

p < .01, \eta^2 = .43; Figure 5.4d), and (5) reaches were initiated at shorter times

F (2,30) = 4.5, \eta^2 < .01, \eta^2 = .33, Figure 5.4b), reaches consisted

While the 20 cm/s velocity condition, 33 infants were included. A similar RM-MANOVA did not reveal

any effects of background or age (all

p's > .1; see Figure 5.5). Yet, a significant effect of age was revealed (Wilks \Lambda = .43, F(8,54) = 3.5, \eta_p^2 = .34) for average velocity (F(2,30) = 6.8, \eta^2 = .31). Post hoc analyses revealed that average velocity was higher for the 6-month-olds as compared to 8- and 10-month-olds (\eta^2 = .31). For the 40 cm/s velocity condition, 32 infants were included. A similar RM-MANOVA did not reveal any effects of background or age (all p's > .1).

**Figure 5.5** Representation of kinematical parameters of right-handed reaches for each background and velocity condition; (a) reach duration, (b) average velocity, (c) number of movement units, (d) relative moment of peak velocity, and (e) object-body midline distance at reach initiation (dtc). *Error bars represent standard error.*

kinematics only those variables that were constrained by object velocity were entered in the analysis of variance with background condition (i.e., same direction, opposite direction, and stationary) as within-subject factor and age as between-subjects factor. Analogous to the reaching mode part, this analysis was performed for each velocity condition separately.

**Right-handed reaches.** For the 20 cm/s velocity condition, 33 infants were included. The RM-MANOVA with average velocity, movement duration, object-infant distance, and number of movement units as dependent variables did neither reveal a main effect of background nor an interaction effect between background and age (both p's > .1; see Figure 5.5). Yet, a significant effect of age was revealed (Wilks \Lambda = .43, F(8,54) = 3.5, \eta_p^2 = .34) for average velocity (F(2,30) = 6.8, \eta^2 = .31). Post hoc analyses revealed that average velocity was higher for the 6-month-olds as compared to 8- and 10-month-olds (\eta^2 = .31). For the 40 cm/s velocity condition, 32 infants were included. A similar RM-MANOVA did not reveal any effects of background or age (all p's > .1).
Left-handed reaches. For the 20 cm/s velocity condition, 34 infants were included. This neither revealed effects of background (all $p > .1$) nor of age ($p = .1$; see Figure 5.6). For the 40 cm/s velocity condition, 22 infants performed left-handed reaches in each background condition. No age or interaction effects were observed (both $p > .1$). Yet, one main effect of background was revealed (Wilks $\Lambda = .58$, $F(10,68) = 2.1$, $p < .05$, $\eta_p^2 = .24$). Separate univariate analysis of variance revealed a main effect of time to contact ($F(2,38) = 6.67$, $p < .01$, $\eta_p^2 = .26$), with longer time to contact in case that the background moved in the same direction as compared to a background moving in the opposite direction ($p < .05$) and a stationary background ($p < .01$; see Figure 5.6d).

**Discussion**

Consistent with the two-visual systems model, adult research suggests a dissociation in information usage for action mode selection and movement control (e.g., Crajé, van der Kamp, & Steenbergen, 2008; Dijkerman, McIntosh, Schindler, Nijboer, & Milner, 2009; van Doorn et al., 2007). More specifically, movement control...
mainly exploits egocentric sources of information, whereas action mode selection is primarily reliant on allocentric sources of information (Michaels, 2000; Milner & Goodale, 2008; van der Kamp et al., 2003). Although previous work suggests that action mode selection and movement control are likely to be dissociated in infants aged 5 months (van Wermeskerken et al., 2011a), it remains unclear whether this dissociation is also information-based. As a first step to resolve this issue, the aim of the present paper was to assess to what degree action mode selection and/or movement control are reliant on allocentric sources of information. To this end, 6- to 10-month-old infants were presented with laterally approaching objects at two speeds (i.e., 20 and 40 cm/s) that moved against a stationary or moving background. Background motion alters allocentric information that specifies the velocity of the object relative to the background. It was hypothesized that if infants’ usage of visual information is functionally dissociated for action mode selection and movement control, background motion would affect infants’ reaching mode, but have no (or only reduced) effects on movement control.

In what remains we will first discuss the general effects of time constraints (i.e., object speed) and the additional effects of background motion on infants’ action selection and movement control. Subsequently, the theoretical consequences of the present findings will be discussed in the context of the two-visual systems model.

**Effects of time constraints on action selection and movement control**

In line with previous observations, infants adjusted their action modes and reaching kinematics to the time constraints imposed by object speed (van Hof et al., 2005; van Hof et al., 2008; von Hofsten, 1983). More specifically, the higher the time constraints (i.e., higher object speed), the more the infants were inclined to reach with the hand contralateral to the side from which the object approached (i.e., right hand), which allows more time to intercept the object as compared to reaching with the hand ipsilateral to the approaching object (i.e., left hand). Yet, infants’ reaching capabilities improve with age, and hence, the effects of time constraints likely diminish with age (see e.g., van Hof et al., 2008). Accordingly, the percentage of reaches with the ipsilateral hand was maintained for the higher object velocity among the oldest infants (see also van Hof et al., 2005).

Reaching kinematics also showed clear and systematic adjustments to different time constraints induced by object velocity. In line with previous findings (e.g., von
Hofsten, 1983), a higher object velocity resulted in an increased average velocity, shorter movement duration, a shorter deceleration phase, and fewer movement units. Intriguingly, reaches with the ipsilateral hand were timed differently than reaches with the contralateral hand. That is, whereas reaches with the ipsilateral hand were initiated at different times to contact (i.e., suggesting a strategy in which the reach is initiated with the object at a constant distance from the interception point), reaches with the contralateral hand were initiated at different object distances from the body-midline (i.e., consistent with a strategy in which the reach is initiated with the object at a constant time from the interception point). This difference in timing might be explained by the increased time constraints relative to the infant’s action capability. That is, if time constraints relative to action capability are low, this allows for both reaches with the ipsilateral hand and a less adaptive timing strategy based on distance. However, if time constraints relative to the infant’s action capability are high, then the chance for success is enhanced by using the hand contralateral to the side from which the object approaches (i.e., buying more time) and the more adaptive timing strategy based on time (which is independent of object velocity; Kayed & van der Meer, 2000; van Hof et al., 2008). Still, additional research, in which infants are presented with objects approaching from both sides with different speeds, would be needed to verify whether the timing strategies are indeed a function of time constraints relative to action capabilities rather than of differences in the control of left- and right-handed movements per se.

Effects of background motion on infants’ action mode selection and movement control

The background motion, which affects allocentric information about the object’s velocity relative to its background while leaving egocentric information about object velocity relative to the infant unaltered, affected both infants’ action mode selection and movement control – albeit that these effects seemed far less pronounced than the effects of manipulating object velocity itself (i.e., time constraints). In particular, background motion affected the use of the contralateral (i.e., right) hand versus the ipsilateral (i.e., left) hand, and the timing strategy. Notice that these variables were also affected by an increase in time constraints (see above). Indeed, the effects of background motion became most apparent in those situations in which the time constraints relative to the reaching capabilities of the infant were highest (i.e., object speed of 40 cm/s). However,
effects of background motion were mediated by age, suggesting that infants’ reaching capabilities also constrained action mode selection. As such, action mode selection of the 10-month-olds was consistent with the use of relative velocity information, i.e., using the contralateral hand more often in case that the background moved in opposite direction (i.e., higher relative velocity). By contrast, the effects of background motion on 6-month-olds’ action mode were reversed. Although affected, the direction of these effects is not consistent with the use of relative velocity information; perhaps these infants were simply distracted by the background motion.

With respect to infants’ movement control, most kinematic variables that were significantly affected by object speed remained unaffected by the background motion. More specifically, average velocity, movement duration, deceleration phase, and the number of movement units were not significantly constrained by changes in relative velocity. However, movement onset of reaches with the ipsilateral hand in the 40 cm/s velocity condition was affected by background motion. Notice that this situation more strongly affords reaching with the contralateral hand and that action mode selection was adjusted accordingly (see above). Yet, not all reaches were performed with the contralateral hand, rather one-third of the reaches was performed with the ipsilateral hand and movement onset of these reaches was affected by the moving background. More specifically, if the background resulted in a lower object velocity relative to its background, then infants initiated their reach at longer time to contact, which is in line with effects of object speed on movement onset observed in adults (see also Caljouw, van der Kamp, & Savelsbergh, 2004; Tresilian & Houseman, 2005; Tresilian, Oliver, & Carroll, 2003).

Interestingly, the current observations are not in complete agreement with previous findings in hitting and catching moving objects against moving backgrounds in adults (Smeets & Brenner, 1995; see also Dessing, Peper, Bullock, & Beek, 2005). That is, in Smeets and Brenner’s study background motion not only affected initiation, but also the unfolding reaching movement (i.e., movement time, peak velocity). The exact reasons for the discrepancy with the current findings is unclear, but it is not unlikely that the large discrepancy in task constraints between the current and Smeets

4 Notice that time to contact of reaches with the contralateral (i.e., right) hand was not affected by the velocity manipulation and thus was not included as dependent variable in the subsequent analyses on the effects of background motion. Hence, to assess whether movement onset of the reaches with the contralateral (i.e., right) hand was affected by background motion, we performed an additional repeated measures ANOVA with time to contact as dependent variable and age as between-subjects variable. This did not reveal any significant effects (all p’s > .1).
and Brenner's study (i.e., participants were instructed to hit a relatively small target, which moved at low speeds on a relatively small screen, as fast and accurate as possible) are pertinent. They certainly make comparisons difficult.

Together, the present findings suggest that in early development movement onset is constrained by allocentric information that specifies the relative velocity of the object, although this was only manifested in situations where time constraints are high. Importantly, once initiated, the unfolding reaching movement remained unaffected by the background motion (i.e., allocentric information).

**Theoretical implications**

The current findings suggest that both action mode selection and movement control exploit allocentric sources of information (i.e., relative velocity), albeit that for movement control exploitation is restricted to movement onset. In terms of the two-visual systems model, this implies that the two visual systems are not completely dissociated at 6 to 10 months of age. Indeed, the present findings are reminiscent of a modification of the two-visual systems model by Glover (2004; Glover & Dixon, 2001). According to this model, both action mode selection and initial parameterization of the movement (which includes the timing of the movement but also movement time, velocity, and acceleration) are guided by a planning system that exploits allocentric information. In contrast, according to the original two-visual systems model by Milner and Goodale the latter function entails vision for movement and is reliant upon egocentric information (Goodale & Milner, 2004a; Goodale, Westwood, & Milner, 2004; Westwood & Goodale, 2003). Hence, the issue boils down to what aspects of action (in the broad sense, i.e., including action mode selection, movement onset, and the control of the ongoing movement) are controlled by the planning or control system (or alternatively, vision for perception or vision for movement).

From an ecological psychology perspective, movement onset would be part of the evolving information-movement coupling (e.g., the movement is initiated when an optical variable reaches a critical value; see e.g., Warren, 1990). That is, the information-movement coupling emerges well before movement onset. If correct, this would suggest that infants' use of visual information for action mode selection as well as movement control (and hence the involved visual systems) are not completely dissociated. If, however, movement onset is part and parcel of movement preparation (as Glover would have it) then a separation in line with a two-visual systems model can
be uphold. Under this scenario, the two functions would be different than originally proposed by Milner and Goodale.\(^5\)

In conclusion, the present findings indicate that infants between 6 to 10 months of age exploit allocentric sources of information for action mode selection and movement control, although in the latter reliance is restricted to movement onset. That is, the unfolding reaching movement was not reliant upon allocentric information sources. In terms of the two-visual systems model as proposed by Milner and Goodale (1995, 2008), this suggests that the two visual systems are largely but not completely dissociated in 6- to 10-month-old infants with respect to their reliance on visual information.

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\(^5\) In this respect, it is intriguing that the empirical evidence for the hypothesis of two dissociated systems is largely restricted to spatial rather than temporal aspects (cf. Willingham, 1998).