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**LA COORDINATION VISUO-MANUELLE CHEZ LE BEBE DE 6 MOIS :  
L'EXPLORATION VISUELLE DIFFERE-T-ELLE EN FONCTION DE LA MAIN  
UTILISEE ?**

**VISUAL EXPLORATION OF REACHING SPACE DURING LEFT AND RIGHT  
ARM MOVEMENTS IN 6-MONTH-OLD INFANTS**

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**Françoise Morange-Majoux** : développement sensori-moteur chez les enfants tout venants et avec autisme, latéralité manuelle, développement du langage.

**Emmanuel Devouche** : Interactions sociales précoces, développement social

**Christelle Lemoine-Lardennois**: Contrôle oculo-moteur, plasticité du système oculo-moteur

**Eric Orriols** : réalité virtuelle, eye-tracking

1 **RESUME**

2 La préférence manuelle et la coordination visuo-manuelle émergent progressivement au cours  
3 de la première année de vie du bébé avec le développement des gestes de préhension. Le but  
4 de cette recherche est de déterminer si l'exploration visuelle au cours des gestes manuels varie  
5 en fonction de la main utilisée, et si oui, d'en décrire précisément ses caractéristiques à l'aide  
6 d'un système d'eye-tracking. Douze bébés âgés de 6 mois ont été observés dans une situation  
7 de préhension (6 essais, 3 avec chaque main). La distribution du regard, la main utilisée, son  
8 mouvement, son ouverture et sa position ont été codés à l'aide du logiciel The observer ®.  
9 Les résultats montrent que les bébés explorent leur espace de préhension différemment en  
10 fonction de la main utilisée : ils regardent plus l'objet lorsqu'ils utilisent la main droite et plus  
11 autour de l'objet lorsqu'ils utilisent leur main gauche témoignant d'une coordination visuo-  
12 manuelle asymétrique précoce.

13

14 **Mots-Clefs** : Latéralité manuelle, coordination visuo-manuelle, exploration visuelle, enfant,  
15 système d'eye-tracking.

16

17 **ABSTRACT**

18 Infant's manual laterality and eye-hand coordination emerge during the second part of the first  
19 year of life with the development of reaching. Nevertheless, little is known about the potential  
20 asymmetric characteristics of this coordination. The aim of this study was to describe visuo-  
21 spatial exploration in 6-month-old infants during reaching, according to the hand used. More  
22 specifically, we examined if the use of the left or the right hand was linked to a specific type  
23 of visual exploration. Gaze direction during goal-directed reaching towards an object placed  
24 on the table was measured with a remote ASL 504 eye tracker (Bedford MA). Twelve babies  
25 aged 6 months were observed during six reaching sessions, alternating three sessions with an  
26 object on the left side of the subject and three with an object on the right side. Gaze direction  
27 and some hand variables (hand activity, hand opening and hand position from the body) were  
28 coded with The Observer software. Results showed that babies visually explore their reaching  
29 space differently according to the hand used: they look more at the object when they use their  
30 right hand and more around the object when they use their left hand; they also look more  
31 often at their left hand than at their right one. These results suggest that an asymmetric visuo-  
32 manual coordination exists as early as 6 months : vision seems to support (1) left hand during  
33 reaching for evaluate distances from object to baby by means of visual feedbacks and (2) right  
34 hand for identify what sort of object is. Results are discussed in light of manual specialization  
35 and specific hemispheric skills at this age.

36 **Key-words:** Manual laterality, visuo-manual coordination, visual exploration, infant, eye-  
37 tracking

38

39

40        **1. INTRODUCTION**

41    Object visuomotor exploration plays a central role in early cognitive development: infants  
42    learn about their physical environment, acquire knowledge to plan future actions and develop  
43    sensorimotor coordination from these visuomotor experiences. The aim of this paper was to  
44    describe how vision participates in reaching, around 6 months, when this hand activity is  
45    well-established but not yet automated. More particularly, we analyzed visuo-spatial  
46    exploration according to the hand used, in order to evaluate if specific visual strategies could  
47    be assigned to manual laterality. In order to specify how visuo-motor coordination is  
48    organized, we also observed visuo-spatial exploration according to the movement of the hand,  
49    its opening and its position to the object.

50    The development of eye-hand coordination like in reaching is a good neuroscientist tool,  
51    widely used to infer relationships between brain and behavior (Luna, Velanova, & Geier,  
52    2008). According to the traditional view of infant reaching development, infants use vision, at  
53    first, to guide the hand towards the target when they begin to reach, around the age of 4  
54    months (Piaget, 1952; White, Castle, & Held, 1964), and then they use the visual error  
55    between hand and target to correct their ongoing reaches (Bushnell, 1985), when the first  
56    successful reaches (grips) appear around 5 months. Between 5 and 7 months, major  
57    developments occur in the timing of infant manual anticipation (such as opening of the hand  
58    during the movement), indicating that grasp control shifts from being manually guided to  
59    being visually guided (Witherington, 2005). However, some results challenge this traditional  
60    point of view: one of the most notable is that sight of the hand is not necessary to make  
61    successful grasps; Clifton, Muir, Ashmead, and Clarkson (1993) have found that infants from  
62    1.5 to 5 months (6 to 25-weeks-of-age) touched objects as in the light as in the dark without  
63    kinematic differences in reaching (Clifton, Rochat, Robin & Berthier, 1994). Moreover,  
64    infants are capable of completing even relatively complex reaches, such as catching a moving

65 object, without visual feedback of the hand (Berthier, Clifton, Gullapalli, McCall, & Robin,  
66 1996; McCarty *et al.*, 2001). Kinematic changes in reaching in the dark have been reported  
67 only in infants aged 15 months (Carrico *et al.*, 2008). However, the fact that infants can reach  
68 in the dark does not mean that they don't use vision when it is available (in the light). We can  
69 suppose that improvement in reaching is probably the result of general improvements in the  
70 use and the integration of different perceptual information in order to make finer a more  
71 reliable movements: infants probably use first, proprioceptive information and then visual  
72 information, which will become more and more indispensable to modulate reaching during  
73 their early development (Thelen *et al.*, 1993; von Hofsten, 1993). We need to have a better  
74 understanding of the role played by vision, especially during the onset of prehension, around  
75 6 months, by differentiating the hand used, which regrettably was not mentioned by the  
76 previous authors.

77 In adults, specific visuo-manual asymmetries are reported: when the subject reaches towards  
78 an object with his/her left hand, his/her eye movements end up earlier on the object and peak  
79 velocity (of eye movements) is reached earlier than when (s)he reaches with his/her right hand  
80 (Lavrysen *et al.*, 2008) and saccades reached the target earlier when accompanying left-  
81 compared to right-hand movements (Helsen *et al.*, 1998a, 1998b; Carnahan *et al.*, 1993).  
82 Goal-directed one hand movements are predominantly controlled by the contralateral cerebral  
83 hemisphere. Traditionally, functional hemispheric specialization is described as right  
84 hemisphere advantage for movement planning and/or attentional aspects and left hemisphere  
85 advantage for processing information during ongoing movement (Hodges *et al.*, 1997;  
86 Carson, 1989). Asymmetries of eye-hand coordination could be explained by the fact that the  
87 right hand/left hemisphere system may have higher efficiency in utilizing response-produced  
88 feedback (Elliott & Chua, 1996). This hemispheric specialization also impacts lateral hand  
89 use: The right hand is involved in the temporal organization of perceptual and/or motor

90 information, during ongoing movements (Flowers, 1975; Bradshaw, Bradshaw, & Nettleton,  
91 1990; Haaland, Elsinger, Mayer, Durgerian, & Rao, 2004), and in the planning of sequential  
92 acts that require response selection, preparation and/or retrieval (Verstynen, Diedrichsen,  
93 Albert, Aparicio, & Ivry, 2005). The left hand is involved in the spatial planning of a task and  
94 in the allocation of attention in space (Carson, 1989; Hodges, Lyons, Cokell, Reed, & Elliott,  
95 1997; Sainburg, 2002). In this perspective, a manual specialization can be defined  
96 independently of handedness: the preferred hand is not always the most relevant according to  
97 task specificities : right-handers perform more rapid and accurate reaches with their left hand in  
98 a pointing task whereas left-handers are more efficient with their right hand in a fine building  
99 task (Gonzalez & Goodale, 2009 ; Lavrysen *et al.*, 2003).

100 If the development of handedness is widely studied, infants' early manual specialization is  
101 less documented and eye-hand coordination asymmetries have as far as we know never been  
102 studied. Some infant studies (von Hofsten, 1979, 1991; Morange-Majoux, Pez , & Bloch,  
103 2000; Hopkins & Ronqvist, 2002; Ronqvist & Domellof, 2006) have shown differences in  
104 the kinematics of right- and left-hand movements: right-hand trajectories are smoother, with  
105 fewer corrections and fewer movement units -identified kinematically as multiple segments of  
106 acceleration and deceleration- than left-hand trajectories. Differences also appear in the  
107 quality of movements: pre-reaching movements are more often performed by the left hand,  
108 whereas reaching and grip movements are more often performed by the right hand (Morange-  
109 Majoux, Pez , & bloch, 2000; Morange-Majoux & Dellatolas, 2010). Finally, infants with a  
110 congenital muscular torticollis develops a hand preference on the opposite side to head-tilt.  
111 Authors concluded that an increased visual control of the hand during early childhood seems  
112 to modulate handedness (Ocklenburg et al., 2010). Such observations are compatible with the  
113 position that the right hemisphere controls close-loop movements dependent on sensory

114 feedback, and the left hemisphere open-loop movements based on well-established motor  
115 programs (Haaland & Harrington, 1989).

116 The Dual Visuomotor Channel theory proposes that visually guided reaching consists of two  
117 temporally integrated movements, the Reach and the Grasp, each mediated by separate  
118 visuomotor pathways, from occipital to parietofrontal neocortex (Arbib, 1981; Jeannerod,  
119 1981, 1999; Rizzolatti *et al.*, 1998; Tanné-Gariépyetal., 2002; Culham & Valyear, 2006;  
120 Cavina-Pratesi *et al.*, 2010; Filimon, 2010; Karl & Whishaw, 2013). Thus, the initial phase of  
121 a reach, mediated by a dorsomedial pathway, serves to transport the hand to the general  
122 vicinity of a target and is in relation with the target's extrinsic properties, i.e. localization and  
123 orientation (*where* pathway). The later phase (grasp), mediated by a dorsolateral pathway, is  
124 devoted to close the hand, in relation with the target's intrinsic properties, with controlled  
125 visual guidance of the hand on the target object, i.e. size and shape (*what* pathway) (Arbib,  
126 Iberall, & Lyons, 1985; Jeannerod, 1981). We have hypothesized that pre-reaching  
127 movements could play a localization role, i.e., provide information concerning the distance of  
128 the object from the body, and that the grip movement could be implied in accuracy. The  
129 behavioral differences between the two hands, observed in babies, could confirm an  
130 asymmetry in information processing between left and right hands: the left hand would be  
131 more involved in the "*where*" pathway and the right one in the "*what*" pathway.

132 As stated above, eye-hand coordination shows early hemispheric asymmetries (Lavrysen *et*  
133 *al.*, 2008) even though at these ages, the use of the right-or the left-hand is task-dependent and  
134 could be in relation with hemispheric specialization (Arbib, 1981; Morange-Majoux &  
135 Dellatolas, 2010). If seeing his/her hand seems to be not necessary for an infant to grasp an  
136 object at 6 months (Clifton *et al.*, 1993, Berthier & Carrico, 2010) this does not mean that  
137 vision does not take a part when it is available. In this perspective, vision could not only  
138 participate in reaching but also select differentiate useful information according to the hand



139 used. We hypothesized that vision could provide more specifically (1) spatial object  
140 information when the infant uses his left hand and (2) intrinsic object information when the  
141 infant uses his right hand. If vision participates to the onset of manual specialization, looks  
142 will be more centered on the object when the right hand is used and looks will be more widely  
143 distributed around the object when the left hand is used. In order to test these hypotheses, we  
144 described spatial distribution of looks (on or around the object) during all the reaching  
145 (including movement and no movement moments) according to the hand used, hand  
146 anticipation and hand localization.

147

## 148 2. METHOD

149 *2.1.Participants:* Twelve healthy 6-month-old (mean age 6 months, 3 days, ranging from 5  
150 months, 20 days to 6 months, 23 days) full-term infants participated in this study (6 males,  
151 6 females). Ten additional infants were tested, but their data were not included in the final  
152 sample, six infants due to technical eye-tracking impairments, two infants because they did  
153 not try to reach the object, and two infants due to fussiness. They were all recruited from  
154 birth lists in the 13th and 14th districts of Paris. All mothers signed an informed consent  
155 form, guaranteeing general anonymous treatment of information. Parents' handedness was  
156 controlled (Edinburgh handedness inventory) : 22 were right-handers and 2 were left-  
157 handers

158 *2.2.Eye-tracking system:* An eye-tracker was used to study very accurately visual exploration  
159 of the baby when he/she had to reach an object. Eye-tracking techniques, in the context of  
160 action, allow to measure how infants explore their physical world, and in particular where  
161 and what they look at, how they observe the scene spatially (object, around the object) and  
162 how many time they look at these parts of the scene, in order to define what strategies they  
163 develop when they want to reach an object. Eye-tracking can provide key insights into

164 real-time dynamics of perception and action, for infants interact with the environment by  
165 the second or the minute. Such rich and detailed information can directly inform about  
166 coordination between cognitive, motor and perceptual processes, and more generally  
167 enrich theories on the development of asymmetries (Corbetta, Guan, & Williams, 2012).  
168 For this study, we used a remote eye tracker developed by ASL (model R6) that provided  
169 eye position coordinates. Head position was recorded with a magnetic tracker, Flock of  
170 Birds (Ascension, Burlington, VT) that provides head position coordinates. The ASL  
171 system can track eye movements directed at scenes defined in 3-dimensional space and  
172 spatially fixed (3D objects located within reaching distance as described in Corbetta *et al.*,  
173 2012). Furthermore, the system was configured to record gaze position on a horizontal plan  
174 (scene plan), i.e. the table in the present study. Using both head position data and gaze  
175 vector position data, the system determines where on the surface the subject is looking  
176 (Eye-Trac 6 Control Unit and User Interface Software Reference Manual, pp 68). The only  
177 constraint was baby's head had to remain stable.

178 *2.3.Apparatus:* The experimental apparatus was composed of an eye-tracking system, a scene  
179 camera above the baby, a minibird eye-tracker, a front webcam, two computers and three  
180 control screens. All components of the experimental apparatus were synchronized and  
181 linked (Figure 1).

182 - Insert Figure 1 about here -

183 Eye-tracking system included a remote optics eye camera that allowed the infant  
184 approximately one square foot of head movement and eliminated the need for head  
185 restraint. This eye-tracker was placed in front of the infant, on the table, at a distance of 50  
186 cm. The infant's line of gaze was measured by computing the pupil-corneal reflection at a  
187 sampling rate of 50 Hz (Figure 1C). The accuracy level was about 0.5° of visual angle,

188 and the resolution was about  $0.25^\circ$  of visual angle. Performance of both eyes was  
189 measured.

190 A scene camera (ceiling camera), placed above the table, captured the table during the  
191 experiment and gave us a still shot of the scene. Live recording of the table was  
192 synchronized on line with the remote optics eye camera by computer which calculated the  
193 superimposition of specific gaze position (symbolized by two crossing lines) and a still  
194 shot of the table (Figure 1A). ASL system was conceived to create a plane projection of  
195 gaze direction vectors and to compute the correlation between calibration points and gaze  
196 direction vectors simultaneously measured. Spatial coordinates were then translated into  
197 eye-tracking coordinates during the calibration phase and calibration points were linked to  
198 the still shot of the scene (see Calibration phase section below).

199 The scene camera also captured the infant's hands activity. The recording was used for  
200 coding hands activity (Figure 1A and 2) with The Observer © software (see Coding  
201 section). Moreover, the superimposition of the still shot with the gazes gave an indication  
202 of when infants looked at their hands.

203 - Insert figure 2 about here -

204 Head position was recorded with a magnetic tracker, Flock of Birds (Ascension,  
205 Burlington, VT). This device has a Mini Bird head tracker that provides head position  
206 coordinates, so that the ASL pan/tilt camera can reconnect to the eye, in case of rapid head  
207 movements (see Gredebäck *et al.*, 2002 and Aslin & Murray, 2004). (see figure .1B)

208 Lastly, a front webcam was added and synchronized to the two other cameras to record  
209 infants' behavior, facial expressions and head orientation (Figure 1B). This additional  
210 camera provided information about the baby's behaviors and allowed to appreciate the  
211 consistency with information of remote eye-tracking detection.

212 The three videos were all captured with the same computer to obtain a synchronized video  
213 recording throughout the experiment (Figure 1).

214 *2.4.Material:* the object to reach was a 2.5 x 2 cm<sup>2</sup> little yellow Kinder© chick graspable by 6-  
215 months-old infants. This toy was placed in front of the infant, on the table, at a distance of  
216 25 cm, just at a reachable distance, inside the tracking window of the ASL system. The  
217 ASL system detects accurately gaze positions on the plan (2D) but the use of a 3D object  
218 generates a decrease in accuracy, due to the object's height (3D). Indeed, the space behind  
219 the object could not be seen from the infant's perspective, and was called the occlusion  
220 area (see figure 1). Thus any gazes at that space detected by the ASL system was in fact a  
221 gaze at the object. This occlusion area was deducible (1.5 cm behind) on the basis of  
222 object's height and the level of the infant's eyes. In order to determine the impact of this  
223 occlusion area on our data, an analysis of the distribution of gazes around the object  
224 revealed that a majority was in front of the object (88%) or on its left- or right-side (11%).  
225 Gazes behind the object were thus very rare (< 1%) and kept out of the study.

226 *2.5.Procedure:* The experiment took place in a quiet room of the Psychology Department at  
227 Paris Descartes University. Infants were seated on their parent's lap, facing a table with  
228 their hands free to move and the body maintained against the adult to limit head  
229 movements of the baby.

230 The parents remained quiet during the entire experiment (approximately 15 min).  
231 Experiment procedure always contained a calibration and a test phases.

232 • *Calibration phase:* Nine calibration target points were used to calibrate the scene plan (see  
233 Figure 3). These nine points were identifiable by landmarks drawn on the table. A  
234 transparent flashing ball (2 cm diameter) was used during calibration phase. This ball was  
235 successively positioned on the nine markers on the table in order to create a bijection of  
236 any point of the scene plan onto the window defined by these nine gaze direction vectors.

237 For each calibration point, the experimenter A (standing behind the remote optic eye  
238 camera) placed the ball on the marker; when a gaze on the ball was detected by the eye-  
239 tracker, experimenter B approved manually on the computer the calibration point  
240 measured. This procedure was repeated for each calibration points. At the end, each of the  
241 calibration point coordinates were translated into visual vectors coordinates and linked to  
242 a scene plan image (scene camera recorded continuously the same scene). In practice, a  
243 cross appeared on the scene plan video recording each time an infant looked on the table  
244 (Figure 1)

245

246 - Insert Figure 3 about here -

247 -

248 • *Test phase:* The little yellow chick was placed on the table, on the right or on the left side  
249 of the baby, inside the scene plan, out of sight of the baby by using a cardboard. An  
250 experimenter stood behind the remote optic eye camera in order to present the test object  
251 to the infants. Six trials were performed, alternatively on the left and the right sides of the  
252 infant in order to induce ipsilateral movements (Fagard, Spelke, & Von Hofsten, 2009;  
253 Morange & Bloch, 1996; Morange-Majoux *et al.*, 2012). First side of presentation was  
254 counterbalanced across infants. At the beginning of each trial an experimenter positioned  
255 a large piece of cardboard (40x60 cm) in front of the baby and a second experimenter  
256 placed the object behind the cardboard, on the table, in the left or right position (the  
257 cardboard was large enough to hide both possible positions of the object). At this stage,  
258 the object and its position were hidden by the cardboard. Then the first experimenter  
259 removed the cardboard, thus uncovering the object. The trial began with the first look at  
260 the object (as identified by the eye tracker), and ended at the *first* contact between the  
261 hand tested and the object (not after reaching or grip because it would have been

262 impossible to determine if the subject looked at the object or his hand). Both eye and hand  
263 activities were recorded during the trial.

264 *2.6.Coding:* Both hand and eye activity data collected by ASL system were coded with the  
265 Observer XT10© software on the video given in Figure 1A, which combined scene video  
266 recording and eye tracking point's projection. We chose to recode eye activity initially  
267 coded by ASL system with the Observer XT10© software in order to (i) check data and (ii)  
268 avoid erroneous data. (i) for example, when the subject looked at the experimenter, ASL  
269 system lost looks. Nevertheless, with the video given in figure 1A, we reconsidered these  
270 lost data and coded them as looks at the experimenter with Observer XT10© software. (ii)  
271 for example, when ASL system identified looks at baby's hand, we systematically checked  
272 with the video given in figure 1A if the hand was posed on the table or aloft. Because of  
273 the position of the scene camera above the hands of the baby, when the hand was aloft,  
274 ASL system identified a look on the hand whereas the look was under the hand on the  
275 table. In this case (very few situations), the look at the hand was reconsidered and coded as  
276 a look at the table with Observer XT10© software. Time-position data were sampled at 25  
277 Hz (25 images per second). Looks and both hands were coded independently, by two  
278 independent observers, blind to the condition and hypotheses. The inter-rater reliability of  
279 the two coders, based on all trials, was 99% for eye coding and 96% for movement coding.  
280 Contentious trials were re-examined by both experimenters and re-coded together until a  
281 100% inter-rater agreement was eventually reached.

282 ➤ Look durations were coded during all the trial according to five areas: (1) on the  
283 object (with a radius of 0.5 cm around the object), (2) around the object (radius  
284 ranging from 0.5 cm to 5 cm), (3) on the table (i.e. elsewhere outside the 5 cm  
285 radius), (4) on the right hand and (5) on the left hand. A look was detected when a

286 cross (intersection between a horizontal line and a vertical line) appeared on the  
287 video: this intersection being a staring (looking) point (see Figure 1A).

288 ➤ Right- and left-hand durations were coded during all the trial according to three  
289 hand characteristics: (1) hand activity (during the trial baby could move or not  
290 his/her arm towards the object); (2) hand opening (widely opened or not) and (3)  
291 localization of the hand with respect to the baby's body (the hand of the baby could  
292 be near him or near the object; we defined two modalities allocentered and  
293 egocentered: the boundary between the two modalities was defined by the median  
294 distance between the body and the object). The word "hand" used in the results  
295 section always refers to the ipsilateral hand according to the object's position.  
296 Analyzes performed on the contralateral hand were systematically specified.

297 All these codings allowed to analyze visuo-spatial distribution according to specific hand  
298 parameters in order to qualify and potentially precise eye-hand coordination.

299 *2.7. Statistics:* Given that trials (72; 36 performed with the left hand, 36 performed with the  
300 right hand) did not have the same durations, they were analyzed according to the total  
301 duration of the trial in terms of percentages (proportions of time), by mean of a two way  
302 repeated measures ANOVA with hands (right / left) and object position (right / left) as  
303 within subject factors, and with partial eta squared values ( $\eta^2_p$ ) as an index of effect size.  
304 For each measure we computed a Shapiro-Wilk test to determine whether the hypothesis  
305 of normality could be rejected. Chi square test was used to analyze cross-tabulated data,  
306 with Cramer's V as an index of effect size. All analyses were done with Stata 14.

307

### 308 3. RESULTS

#### 309 3.1. Hand characteristics

310 All right side objects were reached by the right hand (and reciprocally the left side objects  
311 were reached by the left hand.

312 *3.1.1. Hand activity:* On average, infants did not move their hands during 37% of the trial's  
313 time (ranged from 3,8% to 96,2%). Shapiro-Wilk tests computed for each of the four  
314 measures were all non-significant (all p-values above .08). The two-way repeated measures  
315 ANOVA conducted on the *proportion of time during which the hand remained stationary*  
316 revealed no significant effect of object position ( $F(1,11) < 1$ ;  $p = .94$ ;  $\eta^2_p < .001$ ), but a significant  
317 effect of the hand: the left hand remained more often stationary than the right one (47% vs  
318 30%;  $F(1,11) = 6.60$ ;  $p = .028$ ;  $\eta^2_p = .40$ ; Figure 4) during a trial. A specific analysis carried out  
319 on the contralateral hand revealed that, an object placed on the right side significantly  
320 increased right hand activity and strongly reduced left hand activity (difference of 25 points  
321 between both hands, 50% vs 25%), whereas a presentation on left side activated both hands in  
322 the same way ( $F(1,11) = 5.16$ ;  $p = .047$ ;  $\eta^2_p = .34$ ). Furthermore, only 9% of trials with left  
323 reachings were performed without stationary hand moments, whereas 33% of trials with right  
324 movements did not include any stationary hand moments. In other words, babies kept his/her  
325 hand stationary more often during their left- than their right –hand reachings.

326 - Insert Figure 4 about here -

327 Last, we examined how many trials started with no movement of the hand –left or right- (all  
328 trials began with a look on the table). Analysis showed that 74% of left movements were  
329 initiated first by a look during which the hand did not move, against 47% for the right hand  
330 (difference of 26.3%; IC95% = (3.4; 45.6)). Babies tended to move their right hand  
331 immediately towards the object, as soon as they looked at it, in half of the right hand  
332 movements.



333 3.1.2. *Hand opening*: On average, infants' hands were widely opened 89% of the time.  
334 Shapiro-Wilk test was significant for one measure (right hand / object right;  $p=.0241$ ). The  
335 two-way repeated measures ANOVA, conducted on the *proportion of time where the hand*  
336 *was wide open*, revealed no significant effect, neither of the hand ( $F(1,11)=1.33$ ;  $p=.27$ ;  
337  $\eta^2_p=.11$ ), nor of the object's position ( $F(1,11)=1.11$ ;  $p=.32$ ;  $\eta^2_p=.09$ ), suggesting that  
338 movements have the same profile, whichever hand is used.

339 3.1.3. *Hand position from the body*: On average, 47% of infants' manual activity was  
340 distributed near the object (allocentered). Shapiro-Wilk tests computed for each of the four  
341 measures were all not significant (all p-values above .20). The two-way repeated measures  
342 ANOVA conducted on the *proportion of time the hand was allocentered* revealed no  
343 significant effect, neither for the hand ( $F(1,11)<1$ ;  $p=.54$ ;  $\eta^2_p=.04$ ), nor for the object position  
344 ( $F(1,11)<1$ ;  $p=.66$ ;  $\eta^2_p=.02$ ).

### 345 **3.2. Visuo-spatial exploration during a trial**

346 Automatic detection of staring points by ASL system was performed, on average, 47% of the  
347 total duration of trials (ranging from 29% to 86% depending on the infant). No difference was  
348 found across trials. As described in Method section, we have recoded all eye-tracking data  
349 with Observer XT10© in order to check ASL detection. Five areas into the scene plan where  
350 babies could look at were defined: on the object, around the object, on the table, on their left  
351 hand and on their right hand. In order to examine specifically missing data, we have  
352 completed our analysis by adding babies' looks at the experimenter from the front webcam  
353 video (Figure 1B) with Observer XT10© software. Results showed that babies looked at the  
354 experimenter on average 15% of the total duration of trials, reducing missing data to 38%.

355

356 Figure 5 illustrates the distribution of gazes at the different areas of the scene plan according  
357 to the hand used. When infants used their left hand, they tended to look more around the  
358 object and at their left hand, whereas when they used their right hand, their looks were more  
359 equally distributed toward the object and around it. Otherwise, infants tended to look at their  
360 ipsilateral hand in presence of a lateral reachable object. The two distributions were found to  
361 be significantly different (*Chi square* = 17.64,  $p=.014$ , *Cramer's V* = 0.30).

362 - Insert Figure 5 about here -

363 In order to appreciate more accurately vision control on the different phases of the reaching,  
364 we have examined hand activity during the trial:

365 *3.2.1. When the hand was remained stationary:* Figure 6 presents the distribution of gazes on  
366 the different areas of the scene plan when the hand ipsilateral to the object did not move. The  
367 most remarkable result is that infants looked at mainly around the object when the object was  
368 placed on the left side, and never at their right hand. On the contrary, their looks were more  
369 localized on the object when the object was in the right side. The two distributions were found  
370 to be significantly different (*Chi square* = 22.59,  $p<.02$ , *Cramer's V* = 0.34).

371 - Insert Figure 6 about here -

372 *3.2.2. During hand movement:* Figure 7 presents the distribution of gazes during right- and  
373 left movement. Results showed that whatever the hand used, babies' looks were equally  
374 distributed between object and around it. The most notable result is that babies looked at more  
375 their left hand when they performed a reaching with the left hand than their right one when  
376 they performed a reaching with this one. Both distributions were significantly different (*Chi*  
377 *square* = 32.64,  $p<.01$ , *Cramer's V* = 0.40).

378 - Insert Figure 7 about here -

379 The last analysis was dedicated to examine more accurately gazes on the hands and to answer  
380 to this question: when an infant looks at his hands, what do the hands do ? We compared  
381 proportion of time during which the infant looked each hand considering position, activity and  
382 anticipation of hands. For this analysis, two infants were excluded, because they never looked  
383 at their hands. Shapiro-Wilk tests ran on the 6 distributions revealed that the hypothesis of  
384 normality could be rejected for two measures (left hand allocentered and left hand open;  
385 respectively  $p=.022$  and  $p=.029$ ). When an infant looked at his hand, it was moving half of the  
386 time, with no significant differences between hands (respectively 54% for the left hand and  
387 45% for the right hand;  $t(9)<1$ ;  $p=.68$ ) and allocentered, on average, 70% of the time, with no  
388 significant differences between left and right hands (respectively 71% and 68%;  $t(9)<1$ ;  
389  $p=.62$ ). Finally, the hand was open 82% of the time, with a left hand more often open (96%)  
390 than the right hand (68%), a 28 points difference however not significant ( $t(9)=1.74$ ,  $p=.12$ ).

391

#### 392 4. DISCUSSION

393 The present study aimed to describe how babies visually explore their reaching space in the  
394 presence of a target-object and to determine if this visual exploration varies according to the  
395 hand used and some hand characteristics (manual anticipation, hand activity, hand / object  
396 position). This original eye-tracking design allowed us to investigate new levels of analyses,  
397 by examining precisely the distribution of infant gazes when an object was presented to be  
398 caught. In this context, this study provides the first description, with a remote eye-tracker, of  
399 visuospatial exploration of the infant's reaching space during a movement, according to the  
400 hand used. Several results can be discussed and some conclusions may be drawn.

401 First, result stationary hand s showed a greater activity of the right hand, whatever the  
402 location -right or left- of the object. This was confirmed by the high proportion (1/3) of trials

403 with right hand reaching, always in movement stationary hand. In a previous study, we had  
404 shown that the right hand was always more in motion than the left one (Morange-Majoux *et*  
405 *al.*, 2000). Thus, a context of reaching stimulates right hand movements. This is attested by  
406 others studies (Rönnqvist & Domellöf, 2006; Michel *et al.*, 2006), showing an increase in  
407 right hand use from the age of 6 months, interpreted as the onset of right handedness. In our  
408 study, the greater activity of the right hand probably confirms the beginning of this manual  
409 asymmetry.

410 Second, results about visuospatial exploration provide a great contribution to our  
411 understanding of visuo-manual coordination. Visual exploration of the reaching space is  
412 mainly dominated by two sources of exploration: the space all around the object and the  
413 object itself. The significant result is that an infant does not explore in the same way his  
414 reaching space, according to the hand used and to its activity. During moments where the  
415 hand remained stationary, infants visually explore the space around the object placed on the  
416 left side and look at specifically the object placed on the right side. When they perform a  
417 reaching, their looks are more equally distributed toward the object and around it. We can  
418 assume that looking at the object allows the infant to learn more about the object's physical  
419 characteristics before contacting an object with the right hand. This is compatible with the  
420 better ability of the right hand to catch and manipulate objects observed in previous studies  
421 (Michel & Harkins, 1986; Corbetta *et al.*, 2006; Michel *et al.*, 2006). We can also hypothesize  
422 that looking around the object brings information about its location and its distance from the  
423 body, before reaching it with the left hand. These differences between the two hands, on the  
424 visuospatial exploration of reaching space, reveal not only *asymmetric* visuo-manual  
425 coordination as early as 6 months, but also specific *strategies* according to the steps of  
426 reaching. The well-known studies about hemispheric specialization can enlighten these  
427 results: indeed, the right hemisphere holds an advantage in movement planning and/or

428 attentional aspects (Hodges *et al.*, 1997; Carson, 1989), whereas the left hemisphere is faster  
429 at processing information during the ongoing movement; this information could be either  
430 visual or non-visual (Buekers & Helsen, 2000; Elliott *et al.*, 1999; Roy *et al.*, 1994; Lavrysen  
431 *et al.*, 2003). In this context, when the baby has to perform a left hand movement (right  
432 hemisphere), his/her gazes are distributed all around the object, especially before the  
433 movement, during moments where the hand remained stationary, to evaluate the object's  
434 location. When the baby performs a right hand movement, most gazes are focused on the  
435 object, from the beginning to the end of the trial.

436 In previous studies (Morange *et al.*, 1996; Morange-Majoux *et al.*, 2000; 2010; Morange-  
437 Majoux, 2011), we have shown a lateralization of reaching development : babies use more  
438 often their left hand to perform approach movements, whereas they use more often their right  
439 hand to perform grip movements. These results have been interpreted as evidence for manual  
440 specialization as early as 4-month-olds, The present study brings evidence that vision  
441 participates to manual specialization, in a harmonious, coordinated way: vision is used to  
442 explore all the reaching space when the left hand contributes to evaluate distance and  
443 location; while vision is used to examine an object, when the right hand is used to determine  
444 the object's intrinsic properties. In other words, there is an early asymmetric visuomotor  
445 coordination, probably supported and mediated by different sensorimotor channels (Karl &  
446 Whishaw, 2013; 2014).

447 These results can be compared to researches in adults, which have demonstrated a  
448 specialization in the use of both hands (Carson, 1989; Bradshaw & Nettleton, 1990; Hodges *et*  
449 *al.*, 1997; Sainburg, 2002; Bradshaw *et al.*, 1990; Haaland *et al.*, 2004) and in visuo-manual  
450 coordination (Lavrysen *et al.*, 2008). They are in agreement with the dual visuomotor channel  
451 theory, which proposes that visually guided reaching consists of two movements, a first one,  
452 which transports and guides the hand in relation to the extrinsic features (location) of the

453 target, while another one opens, shapes and closes the hand on the target, in relation with its  
454 intrinsic features (size, shape). In this perspective, our study shows that each movement is  
455 allocated to a specific hand. One prediction of the dual visuomotor channel theory of  
456 reaching, is that development should feature independence in the maturation of the two  
457 movements. Researches have shown that movements to locate object occur before movements  
458 to grip objects (Von Hofsten, 1984; Savelsbergh & van der Kamp, 1994; Morange & Bloch,  
459 1996; Morange-Majoux *et al.*, 2000; 2010). During development, reaching and grasping  
460 become integrated in a seamless visually guided act. We argue that these behavioral  
461 differences between the two hands, observed in babies, could confirm an asymmetry in  
462 information processing between the left and the right hands: the left hand would be more  
463 involved in the “*where*” pathway and the right one in the “*what*” pathway.

464 Third, another notable result concerns gazes on the left hand (31%), especially during moving  
465 moments. It will be interesting in a future study to determine at what time during the trial  
466 these looks on the left hand *in progress* appear. Numerous researchers have investigated the  
467 role of vision in prehension (Bushnell, 1985; Carrico et al., 2008; Berthier *et al.*, 2010;  
468 Hofsten, 1991): some of them propose that infants use sight of the hand to guide early  
469 reaching (Piaget, 1952; Bushnell, 1985), others consider that sight of the hand is not necessary  
470 to make successful grasps (Clifton et al., 1994; Carrico et al., 2007). As we have suggested,  
471 babies use visual information when it is available even if babies can reach objects without the  
472 sight of their hand. Our results show that when babies can see their hands, they significantly  
473 look at their left hand more than their right hand during reaching. This increase of gazes at the  
474 left hand could be interpreted as a great left hand expertise for visuospatial processes: infants  
475 look at the most visuo-spatially adapted hand in order to evaluate distances (i.e. from their  
476 hand to the object) and localize an object. Furthermore, analyzes regarding the number of  
477 wig-wag between an object and the left hand is twice higher than with the right hand

478 confirming its role to evaluate distances. These results allow us to draw a complex  
479 asymmetric visuo-manual coordination, which appears as early as 6 months: when babies use  
480 their left hand they tend to look at around the object before to initiate their reaching in order  
481 to evaluate and determine the distance, then they perform their movement while looking their  
482 left hand and doing wig-wag between object and the left hand. When babies use their right  
483 hand, they tend to look at around and on the object, before and during the movement. Vision  
484 supports left hand during reaching for evaluate distances by means of visual feedbacks. This  
485 visuo-manual coordination appears still integrated and favors knowledge about physical  
486 environment. This visuo-manual coordination probably finds its origin in hemispheric  
487 specialization, as Lavrysen and collaborators (2008) have suggested. The left hand system  
488 may be more effective at using visual feedback and retro-control via right hemisphere and the  
489 right hand system may be more effective at using feedforward and predictive control via left  
490 hemisphere (Roy and Kalbfleisch, 1994). Previously, we have showed that left-hand made  
491 numerous changes in direction suggesting a spatial scanning, such adjustments requiring more  
492 time (Morange-Majoux et al., 2000). Results achieved in the dark or without visual feedback  
493 of the hand (Berthier *et al.*, 1996; McCarty *et al.*, 2001) are not contradictory with our results:  
494 at this age, vision is not used to guide movement but probably more to inform the baby on  
495 object extrinsic properties (where it is ?) and intrinsic properties (what is it ?). It would be  
496 interesting to examine manual laterality in the dark and in particular, to determine if the use of  
497 the left hand is disturbed or not (without possibility of visual feedbacks) and to compare  
498 kinematics of left- and right reaching in light and dark in order to examine not only the onset  
499 of visuo-manual coordination but also its asymmetry. Moreover, it will be interesting to  
500 describe longitudinally the development of the role of vision according to the hand used.

501 In addition, results showed that when an object is presented in front of a baby, his/her hands  
502 are, most of the time, widely open, indicating that the baby is ready to reach out to the object,

503 which confirms what had been observed in others studies ((Fagard, 2000; Fagard & Pezé,  
504 1997; Hofsten & Fazel-Zandy, 1984). Sacrey and Whishaw (2010) have shown that collection  
505 (hand shape in which digits are lightly flexed and closed) becomes increasingly prominent  
506 from 1 to 6 months. It replaces a clenched fist that was typically held proximal to the upper  
507 torso. This collation development is probably the precursor of other hand shaping movements,  
508 like skilled movements of grasping and reaching.

509 In conclusion, we argue that eye-tracking may be used in the context of action. It raises novel  
510 questions about the development of visuo-manual coordination. It allows to explore with good  
511 accuracy where infant direct their gaze on a scene (Corbetta *et al.*, 2012), what they look at  
512 and how many times they do so. We are aware that the loss of eye-tracking data (38%) during  
513 head turns or others behaviors preventing eye capture is a serious limitation of our study.  
514 Head-mounted eye-trackers do show advantages to study infant perception in more natural  
515 and less-constrained environments (Corbetta *et al.*, 2012).



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696 **List of Figures**

697

698 **Figure 1:** Experimental design. Eye-tracking system was configured to record looks on a horizontal  
699 plan. 1A: Scene plane recorded by the scene camera. Live recording of the table was synchronized on  
700 line with the remote optics eye camera by computer which calculated the superimposition of specific  
701 looks (symbolized by two crossing lines) and the fixated plan of the table. 1B: view of front webcam  
702 synchronized to the two other cameras to record infants' behavior, facial expressions and head  
703 orientation (infant with a Mini Bird Head tracker). 1C: infant's line of gaze was measured by computing  
704 the pupil-corneal reflection at a sampling rate of 50 Hz.

705 **Figure 2:** Examples of images recorded by scene camera allowing to record infant's hands activity  
706 useful for the coding of hands activity. The superimposition of the fixed plane with the looks  
707 (intersection of horizontal and vertical black lines) on video recording scene plane gave indication of  
708 when infants looked at the hands.

709 **Figure. 3:** Calibration phase: 9 calibrations points were used. This most frequently used method  
710 provides robust and accurate data under most circumstances (a). A Flashing Ball was used to visually  
711 attract the subject: for each nine points, the flashing ball was put on a calibration point (examples in b  
712 and c). For each calibration point, when the infant looked at the ball and we had simultaneously a  
713 cross given by the eye-tracker indicating a gaze, another experimenter approved the calibration point  
714 and manually confirmed it on the computer. The target-object was placed on the table, on the right or  
715 on the left of the baby, inside the scene plane.

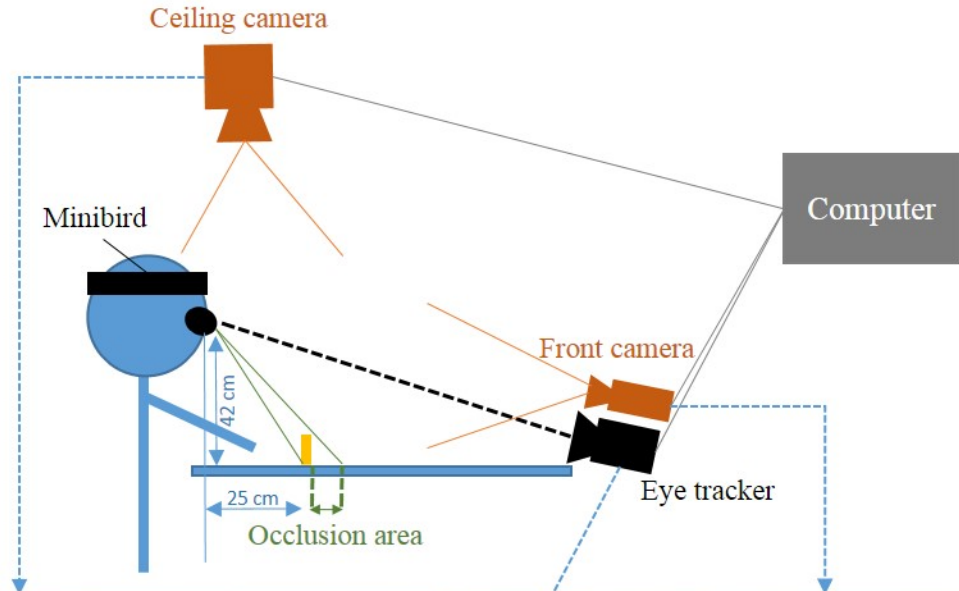
716 **Figure 4.** Proportion of time the left- and the right-hand remained stationary

717 **Figure 5:** Distribution of gazes (in %) according to the hand tested.

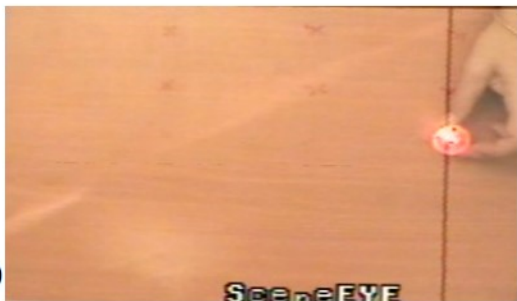
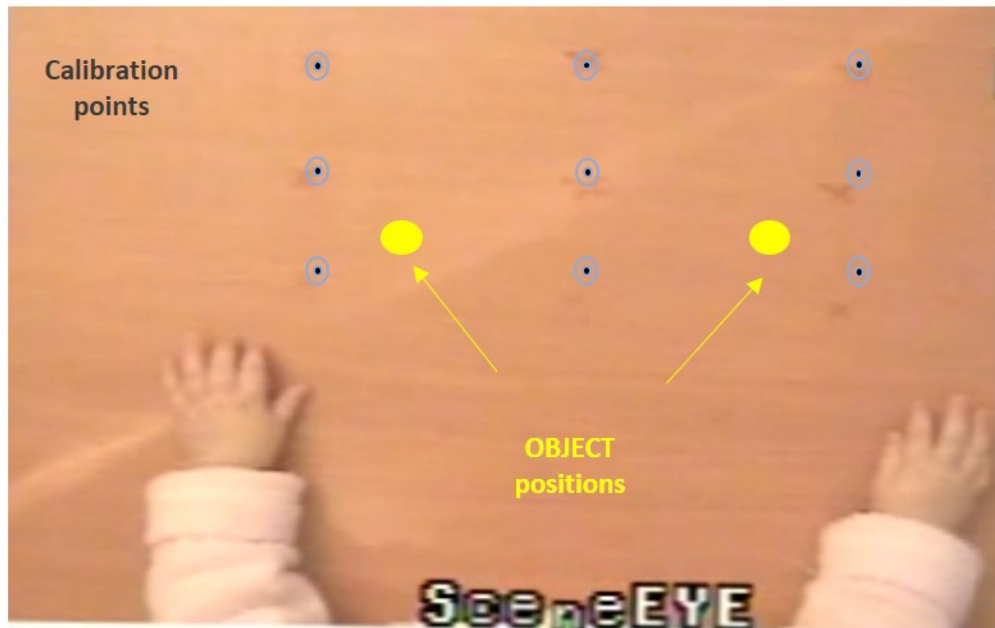
718 **Figure 6:** Distribution of gazes (in %) when the hand tested remained stationary according to the hand  
719 tested.

720 **Figure 7:** Distribution of gazes (in %) when the hand tested is moving according to the hand tested.

721







Proportion of time the hand was  
unmoving

