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Bimanual coordination in typical and atypical infants: movement initiation, object touching and grasping

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Abstract

The development of bimanual actions reflects perceptual, motor and cognitive processes, as well as the functional connectivity between brain hemispheres. We investigated the development of uni- and bimanual actions in typically-developing (TD) infants and infants with Down syndrome (DS) while they reached for objects with varying sizes. Eight TD infants and seven infants with DS (ages 4 to 8 months) were tested at several stages of reaching experience. Movement strategies at movement initiation, object touching and grasping were recorded. With reaching experience, typical infants increased ability to anticipate reaching strategies, and independent use of the hands according to task demands. Strategies used by infants with DS were mostly compensatory rather than anticipatory, and showed a weaker tendency for interlimb coupling at early ages. These differences may underlie functional limitations, and should be subject to early intervention.

Keywords

reaching; grasping; interlimb coordination; Down syndrome; object properties

1. INTRODUCTION

Typically-developing infants start to reach around 3-4 months of age (Thelen et al., 1993; Von Hofsten, 1991). By the time of reaching onset, infants frequently use bimanual strategy with the arms in synchronized and symmetric trajectories (Corbetta & Thelen, 1996; Fagard & Jacquet, 1996). The ability to select uni- or bimanual reaches based on object properties is progressively refined (Rocha, de Campos, Silva, & Tudella, 2012), and asymmetrical bimanual manipulation of objects becomes prominent at later ages.

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While early reaches show a strong innate tendency for interlimb coupling (Cardoso de Oliveira, 2002), the maturation of interhemispheric connections seems to be related to emergency of asymmetrical manipulation of objects, which is rudimentary by 7 months of age and refined by 13 months (Kimmerle, Ferre, Kotwika, & Michel, 2010; Nelson, Campbell, & Michel, 2013). However, although there is a significant amount of studies addressing the developmental trajectory of uni- and bimanual movements and the symmetry/asymmetry of hand position at the beginning of the reach and during the trajectory towards the object, there is limited information on how the two hands are coordinated at different stages of the reach (i.e., the beginning of the movement, object touching and grasping), especially at younger ages. In addition, very little is known about the performance of infants with developmental disorders.

Because the development of interlimb coordination reflects the maturation of cerebral areas and of perceptual-cognitive processes, understanding manual coordination when infants touch and grasp objects may reveal their ability to plan movements and to use sensory information to guide action. In this study, we will investigate the strategies used at the beginning of the reach, at object touching, and at the moment of grasping comparing typically-developing infants to infants with Down syndrome (DS). Besides motor delay (Tudella, Pereira, Basso, & Savelsbergh, 2011) individuals with this syndrome usually have altered cerebral organization, e.g., abnormal corpus callosum (Heath, Grierson, Binsted, & Elliott, 2007), reduced number of neurons at cortical layers II and IV (Wisniewski, 1990), and delayed post-natal myelination (Nadel, 2003). All of these can affect the organization of uni- and bimanual movements and the adjustments necessary to grasp objects with different properties.

Another goal of this study is to investigate the strategies used by infants towards objects with different sizes and the longitudinal changes in these strategies after reaching onset. It has been shown that the reaching skill and experience are determinant to the performance of these movements (Carvalho, Tudella, Caljouw, & Savelsbergh, 2008; de Campos, Costa, Savelsbergh, & Rocha, 2013). Therefore, the participants in this study will be matched by reaching onset instead of chronological age, in order to even the effect of reaching experience. Given that by the time of reaching onset and in the following month infants perform jerky movements that are not well tuned to object properties (Rocha, Silva, & Tudella, 2006b; Thelen, et al., 1993), infants at those ages will be defined as *beginners*. About two months after reaching onset, reaches become smoother and straighter (Rocha, Silva, & Tudella, 2006a; Spencer, Vereijken, Diedrich, & Thelen, 2000), therefore this level will be defined as *intermediate*. About three months after reaching onset, infants become consistent at adjusting their movements to object properties, performing appropriate proximal and distal adjustments (de Toledo, de Almeida Soares, & Tudella, 2011; Fagard & Jacquet, 1996; Fagard & Pez, 1992), therefore this level will be defined as *skilled*.

As infants with DS have slower interhemispheric connections (Heath, et al., 2007), we hypothesize that at all the stages manual strategies in the DS group may be less adjusted to the object properties. In addition, because infants with DS may take longer to learn from experience (de Campos, et al., 2013; Polastri & Barela, 2005) changes in uni- and bimanual strategies may be delayed in this group compared to typical infants.

2. MATERIAL AND METHODS

2.1 Participants

Eight typically-developing infants (TD group) and seven infants with Down syndrome (trisomy-21; DS group) born full-term, with birth weight higher than 2,500 g and Apgar index higher than 7 in the first and 10 in the fifth minutes were included in the study. All the participants in the DS group attended early intervention programs since two months of age and throughout the study period. The study was approved by the local Ethics Committee and the parents/guardians of all the participants signed an informed consent.

2.2 Procedures

Participants were longitudinally tested at 4, 5, 6, 7 and 8 months of age. As mentioned earlier, we defined as *beginner* level both the first assessment from 4 months onwards that the infant reached for the objects and the following month. For typically-developing infants, reaching started either at age 4 (n=7) or 5 months (n=1) months; for infants with DS reaching started at age 4 (n=3), 5 (n=2) or 6 (n=2) months. The assessment that happened two months after the first reach was defined as *intermediate* level. Assessments performed when the infants had been reaching for at least three months were defined as *skilled* level. The chronological ages that represent each stage for individual participants are shown in Table 1.

At each test, infants were positioned in a reclined chair with trunk support. Four spherical objects (Rocha, et al., 2012) were used as stimuli: two large (12.5 cm in diameter) and two rigid (5 cm in diameter). The objects were presented at infants' midline, shoulders' height and arms' length. After each reaching movement, the object was presented again until seven trials were performed. Three cameras recorded the entire assessment. One was positioned above the testing area, and two were positioned on each side (Rocha, et al., 2006a). The videos were watched afterwards by one examiner for coding of the variables described at section 2.3. To test the reliability of the coder, a subset of images (3 different infants, total of 180 reaches) was analyzed by two other experienced coders. The total inter-rater agreement for reaching variables reached 93.3%.

2.3 Data analysis

A reach was defined as the uninterrupted movement of one or the two arms towards the object that resulted in object touching (Rocha, et al., 2006a). In some trials, object touching was followed by grasping, which was defined as fingers flexion and object enclosure (Toledo & Tudella, 2008).

Regarding interlimb coordination, reaches were categorized at the following stages:

- Initiation and trajectory of the reaching movement as: *synchronous bimanual*, when both arms either started to move simultaneously or with a delay no longer than 3 frames (approximately 48 ms) and the limbs moved together for at least 50% of the trajectory (Rocha, et al., 2006b); or *asynchronous bimanual*, when both arms started moving with a delay of 4 to 20 frames (approximately 64 to 320 ms) between each other, as long as the

limbs moved together for at least 50% of the trajectory (Rocha, et al., 2006b); or *unimanual*, coded under one of the following conditions: only one arm reached for the object; both arms moved with a delay that was longer than 320 ms; movement of one arm towards the object while the opposite arm performed random movements not directed towards the object; movement of the second hand started after the first hand had touched the object (Rocha, et al., 2006b).

- Object touching was categorized as: *symmetrical bimanual*, when both hands touched the object either simultaneously or with a delay no longer than 48 ms; or *asymmetrical bimanual*, when both hands touched the object with a delay that was longer than 48 ms, as long as the second hand touched before the first hand grasped the object or interrupted the contact; or *unimanual*, coded either when only one hand touched the object or when the second hand touched it after the first had grasped or interrupted the contact.

- Grasping was coded as: *bimanual*, when the infant used both hands to grasp and take the object from the examiner's hands; or *unimanual*, when only one hand was used to grasp; and *Failure*, when the infant failed to grasp the object.

The median count of behaviors at each experience level was used for statistical analysis. The Mann-Whitney test was used to compare the median count of each category of behaviors across groups considering each object size (small x large) at each experience level. SPSS 19.0 was used for all analyses, and a 5% significance level was used.

3. RESULTS

The results presented below include the analysis of 1131 reaching movements, 456 of them performed by infants with Down syndrome. Subheadings within this section refer to the points of the reaching behavior that were coded for uni- and bimanual strategies.

3.1 Initiation and trajectory of the reaching movement

Figure 1 shows the median count of the movement initiation configurations. The comparison between groups revealed that in the reaches towards the large objects the TD group performed more synchronous bimanual movements than the DS group ($p=0.042$) at the intermediate level. For the small objects, differences were found between groups at the skilled level, when infants with DS performed less unimanual movement initiation ($p=0.009$) than typical infants. Also at the skilled level, the group with DS performed more bimanual initiation ($p=0.016$), specifically more movement initiations that were asynchronous bimanual ($p=0.042$) than the TD group.

3.2 Object touching

At the beginner level, the comparison between groups showed that in the reaches towards the large objects, infants with DS performed less bimanual object touching than typically-developing infants ($p=0.03$). At the intermediate level, infants with DS performed less symmetrical bimanual object touching ($p=0.042$) than typical infants. No differences in the reaching strategies were found when comparing the groups at the skilled level. For the small objects, at the beginner level infants with DS performed less asymmetrical bimanual

touching ($p=0.041$) than typical infants. At the skilled level, infants with DS performed less unimanual object touching ($p=0.009$) than the typical group. The median count of each category is shown in Figure 2.

3.3 Grasping

At the intermediate level, infants with DS performed less unimanual grasping ($p=0.032$) and more bimanual grasping ($p=0.009$) when reaching for the small objects compared to the typical group, as shown in Figure 3. No differences between groups were found in grasping strategies at other experience levels and for the large objects.

4. DISCUSSION

This study investigated uni- and bimanual strategies used by typically-developing infants and infants with Down syndrome when reaching for objects with different sizes, in several time points after reaching onset. The results show that in both groups there were changes in the strategies used as infants became more experienced in reaching, but the infants with DS used strategies that were less adjusted to object size, and showed less anticipatory adjustments compared to the typical infants.

In both groups, movement initiation was predominantly unimanual (Figure 1). However, there were differences between groups in the strategies for both large and small objects. Compared to infants with DS, typical infants performed more synchronous initiation towards the large objects at the intermediate level, which is indicative of larger interlimb coupling during this stage. Infants with DS performed less unimanual strategies than the typical group at the skilled level, with a higher frequency of asynchronous bimanual initiation. Fluctuations in the predominance of bimanual strategies have been previously reported (Corbetta & Thelen, 1996; Fagard & Peze, 1997) and are consistent with the current results for the typical infants. The infants with DS showed a weaker tendency to couple their upper limbs compared to the typical group at the intermediate level, which may be related to the delayed maturation of interhemispheric pathways (Heath, et al., 2007). In addition, while bimanual strategies became less common as typical infants became more skilled, infants with DS were delayed in using unimanual strategy in an adaptive fashion when reaching for the small objects. Adjustments performed at movement initiation are possible based on visual information and previous knowledge about the information (Jeannerod, 1984). Therefore, the results suggest poor use of sensory information to anticipate interlimb configuration among infants with DS.

The analysis of object touching strategies revealed again a peak in symmetrical behaviors in the typical group at the intermediate level in the reaches towards the large objects that was not seen in the DS group. Despite this peak in symmetrical behaviors, at all ages the typical infants selected unimanual strategy for the small objects, while the frequency of this strategy was lower in the DS group, reaching significant difference at the skilled level. Therefore, the results suggest that not only the anticipation of the strategy by the time of movement initiation, but the online correction of the movement was also impaired in this group, resulting in poorly adjusted touching.

Regarding object grasping, the strategies used when grasping the large objects seem to be similar between groups. The only group difference found was that infants with DS performed less unimanual grasping of the small objects than typical infants at the intermediate level. This finding may be explained by their smaller hand sizes (Jover, Ayoun, Berton, & Carlier, 2010), a possible reason why grasping a large object with the two hands would increase chances of success. No differences were found in the skilled level for unimanual grasping. However, considering that unimanual adjustment was used less in the DS group when touching the object, we can infer that infants with DS are likely to perform compensatory adjustments based on tactile information from the object, adjusting the grasping after object touching.

Taken together, the results from movement initiation, object touching and grasping indicate a trend towards uncoupling the upper limbs as typical infants become more experienced in reaching. When infants in this group became more experienced in reaching, the use of bimanual strategies, both symmetrical and asymmetrical, decreased. These findings are consistent with reports of stronger interlimb coupling in young infants, which has been attributed to an innate tendency of the motor cortex to generate synergistic impulses to homologous group muscles (Kelso, Putnam, & Goodman, 1983). These synergies are inhibited once selective motor connections are refined, which enables the emergence of independent arm (Sukal-Moulton, Murray, & Dewald, 2013). Another factor possibly contributing to the findings in the typical group are changes in the motor repertoire. Infants around the time of reaching onset are strongly oriented towards the midline. As better postural control in the seated posture is acquired, less synchrony between arms is seen, and the infants become able to use their arms independently during goal-directed tasks (Rochat & Goubet, 1995).

In infants with DS, slower interhemispheric communication may have impaired the formation of muscle synergies, resulting in temporally disparate activation of upper limbs. Another factor possibly leading to this finding may be the lack of midline orientation in individuals with DS (Pereira, Basso, Lindquist, Silva, & Tudella, 2013; Tudella, et al., 2011). The delayed acquisition of seated postural control (Pereira, et al., 2013) could limit the performance of unimanual movements, however, since in this study trunk support was provided, it may not be a factor in the results observed. In addition, the increase in asynchronous movement initiation and asymmetric object touching over time can represent a trend towards more independent arm movements in the group with DS.

When comparing the groups at each object size, the results indicate that the strategies used by infants with DS were less adaptive. At all experience levels infants with DS fell behind the typical group in the ability to select unimanual strategies towards the small objects at all stages of the reaching movement. We conclude from the results of the current study the interlimb coordination in infants with DS is poorly modulated by sensory information.

In previous studies, we observed that reaching movements performed by infants with DS show poor spatio-temporal adaptability to object size, and that manipulation and exploration of small objects is challenging for these infants (de Campos, et al., 2013; de Campos, Francisco, Savelsbergh, & Rocha, 2011). However, the characteristics of only one limb has

been previously analyzed, therefore limited conclusions could be drawn regarding the mechanisms underlying the functional limitations. The results from the current study indicate that interlimb coordination is different, and that sensory and motor constraints may limit the selection of the strategy leading to successful completion of the task. One limitation of the study was the choice of size for large objects. It is possible that, if the objects were even larger, more bimanual reaches would be elicited and we could have more insights into the organization of interlimb coordination.

Nevertheless, the results point that while typical development is characterized by increased ability to modulate reaching from the movement initiation and by increased use of the hands in a dissociate fashion when the task demands so, infants with DS take longer to select adaptive uni- and bimanual strategies, and that these strategies may be mostly compensatory rather than anticipatory. Infants with DS also showed a weaker tendency towards interlimb coupling at earlier ages, although bimanual strategies became more similar to typical infants at later stages as shown by the reaches toward the large objects. Information of therapeutic interest provided by this study includes the need for offering objects with different sizes during stimulation sessions. It was shown that large objects typically elicit bimanual strategies from the beginning of the reach, and that small objects elicit unimanual strategies. Therapists can use this knowledge to plan desired outcomes.

4. CONCLUSION

Interlimb coordination is differently organized in typically-developing infants and infants with Down syndrome. Typical infants change their configuration of movement initiation, object touching and grasping and change from coupled movements to strategies that are tuned to object properties in an anticipatory fashion. On the other hand, infants with DS may rely more on changing grasping configurations in a compensatory fashion, performing movements that are less adjusted to object properties. They seem also need longer time to refine uni- and bimanual strategies, which may be one factor leading to functional limitations since early ages.

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HIGHLIGHTS

- Uni- and bimanual movements have a compensatory character in Down syndrome.
- Uni and bimanual strategies in Down syndrome are less adjusted to object properties.
- Typical infants change uni-and bimanual strategies in anticipation to grasping.
- Typical infants change from coupled movements to object-oriented strategies.

Figure 1.

Median values for each category of movement initiation (AB= asynchronous bimanual; SB= synchronous bimanual; Uni= unimanual) in the reaches towards large and small objects performed by typically-developing (TD) infants and infants with Down syndrome (DS). Dots represent outliers; stars represent significant differences between groups.

Figure 2.

Median values for each category of object touching (BAT=bimanual asymmetrical; BST=bimanual symmetrical; Uni= unimanual) in the reaches towards large and small objects performed by typically-developing (TD) infants and infants with Down syndrome (DS). Dots represent outliers; stars represent significant differences between groups.

Figure 3.

Median values for each category of grasping in the reaches towards large and small objects performed by typically-developing (TD) infants and infants with Down syndrome (DS). Dots represent outliers; stars represent significant differences between groups.

Table 1

Age, in months, corresponding to each stage of reaching experience for individual participants.

Participant	Group	Stage of reaching experience (age in months)		
		Beginner	Intermediate	Skilled
1	TD	4 and 5	6	7 and 8
2	TD	4 and 5	NT	NT
3	TD	5*	7	8
4	TD	4 and 5	6	7 and 8
5	TD	4 and 5	6	7**
6	TD	4*	6	7 and 8
7	TD	4 and 5	6	7 and 8
8	TD	4 and 5	6	8**
9	DS	4 and 5	6	NT
10	DS	5 and 6	7	8
11	DS	4 and 5	6	7 and 8
12	DS	5 and 6	7	8
13	DS	6 and 7	8	NT
14	DS	4 and 5	6	7 and 8
15	DS	6 and 7	8	NT

Legend: - NT= not tested due to participant's absence;

* = first assessment that the participant performed reaches, absence in the following month;

** = participant was absent in the next age that would be considered skilled.