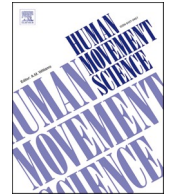




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# Impairment in understanding grasping movements in egocentric and allocentric perspectives in children with cerebral palsy due to periventricular leukomalacia

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## ABSTRACT

Recognizing and understanding the actions of others through motion information are vital functions for social adaptation. Conditions like neurological disorders and motor impairments can impact sensitivity to biological motion, highlighting the intricate relationship between perceiving and executing movements. Our study centred on assessing the ability of children, encompassing both those with typical development and those diagnosed with cerebral palsy due to periventricular leukomalacia (PVL), to discriminate between depicted grasping of a small cylinder and a large cube. This discrimination task involved observing a point-light animation depicting an actor grasping the object, presented from either an allocentric perspective (observing others) or an egocentric viewpoint (observing oneself). Notably, children with PVL exhibited a pronounced and specific impairment in this task, irrespective of the viewpoint, as evidenced by thresholds increasing by nearly a factor of two. When comparing this impairment to difficulties in form or motion perception, we identified a robust correlation between egocentric biological motion and form sensitivity. However, there was no similar correlation between motion and biological motion sensitivity, suggesting a deficit in the visual system rather than the visuo-motor control system. These findings contribute to our understanding of the intricate interplay between motor and visual processing in individuals with congenital brain lesions, shedding light on the significant involvement of the visual system in cases of PVL.

## 1. Introduction

The capacity to perceive, recognize, and comprehend the movements of others through motion information is vital for navigating the social realm and ensuring our survival. Our visual system can distinguish human actions through solely joint motion, a phenomenon known as biological motion (BM) perception (Hirai & Senju, 2020; Johansson, 1973), which underlies the mechanisms of action perception. According to the latest findings, various distinct visual regions, particularly in the superior temporal sulcus (STS),

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appear to be the most activated by biological motion sequences. The STS is located in a region where dorsal and ventral visual information converges (Vaina et al., 2001). Additionally, areas of the frontal cortex, such as the premotor areas situated in human “mirror system” areas for action, show activation in response to this type of stimuli (Fadiga et al., 2005; Saygin et al., 2004). Several studies investigated the swift developmental trajectory of BM perception. In line with this, some authors suggested the possibility of a predisposed and experience-independent perceptual mechanism for the detection and analysis of BM (Simion et al., 2008). On the one hand, this innate visual inclination could suggest an intrinsic ability within the visual system to process human motion, but on the other hand, the research of Fox and McDaniel (Fox & McDaniel, 1982) showed that infants 4 to 6 months of age, but not infants of 2 months of age, exhibit a preference for biological motion patterns, preferring a point-light walking figure over dynamic noise or an inverted configuration. These data support the hypothesis that, although the BM perception mechanism develops very early in life, it could be partially intrinsic and partially acquired through experience. Bertenthal et al. (Bertenthal et al., 1987) corroborated these findings, demonstrating that infants aged 3–5 months can discern a point-light walker from displays featuring jumbled moving dots or configurations lacking natural occlusion relationships during a gait cycle (Bertenthal et al., 1985). Additionally, some evidence indicates that infants aged 5 to 7 months can coordinate visual and proprioceptive sensory information of their actions in normal and changed viewing settings when exposed to point-light displays of lower body movements (Schmuckler & Fairhall, 2001).

This is in line with the findings of Daum and collaborators (Daum et al., 2016), which highlighted that infants’ perception of grasping actions is still flexible and malleable through short sequences of observations during the first months of age. Indeed, infants from 5 months of age can infer the goal-directedness of an observed grasping hand through the emergence of covert shifts of attention mechanisms (Daum & Gredebäck, 2011). These findings suggest an effect of experience on BM perception that could be explained by a maturation of the neural networks at play during infancy (Lemaire & Vallortigara, 2023). Based on these observations, the factors that underlie this preference remain the subject of ongoing debate. In this regard, a recent study by Hirai and Senju (Hirai & Senju, 2020) introduced a two-process theory of BM processing. The researchers propose that the initial system, termed the ‘Step Detector,’ is responsible for processing local foot motion and information related to feet below the body, particularly specific to vertebrates. This system is thought to be minimally influenced by postnatal learning and engages subcortical networks. The second system, known as the ‘Bodily Action Evaluator,’ focuses on processing the finer global structure-from-motion and is specific to conspecifics, relying on gradual learning processes within cortical networks.

As a matter of fact, several findings also suggest that the development of BM sensitivity is based on visuomotor experiences for a long time during the postnatal period, despite the early emergence of this skill. For instance, studies by Pavlova et al. (Pavlova et al., 2001) and Hadad et al. (Hadad et al., 2011) reveal a delayed maturation of BM perception in children, with adult-like performance observed only at 12–14 years of age. Similarly, Tinelli et al. (Tinelli et al., 2017) observed a gradual enhancement in the ability to discern object properties from the observation of BM in a grasping action, progressing from 7 to 18 years of age. According to these authors, the developmental course of BM perception of grasping is gradual and similar if this is proposed from an egocentric or allocentric view (that is, observing the action of others or self). However, only late in adolescence does the preference for an egocentric viewpoint become predominant, suggesting that these differences in perspective could engage distinct neural mechanisms and cognitive processes, resulting in differences in BM perception. This improvement during development aligns with advancements in fine motor control (Bassolino et al., 2015; Corbetta & Snapp-Childs, 2009; Virji-Babul et al., 2012).

Likewise, research involving individuals affected by neurological disorders provides additional insights into postnatal development. Given the intimate bi-directional connection between visual and motor cortices, it is expected that individuals with movement disorders, particularly if congenital or early-onset, would exhibit limited visual processing of movements. Arrighi et al. (Arrighi et al., 2011) conducted a study measuring sensitivity to detect people walking in point-light displays among subjects with peripheral motor injuries at the spinal level during adolescence. The patients displayed sensitivity nearly three times lower than that of healthy controls in the task of discriminating the direction of a BM. Furthermore, the same patients showed less sensitivity (~40 %) to simple translational movement compared to the discrimination of the orientation of static gratings, which was preserved. These findings imply a robust interaction between motion perception and production, implicating shared algorithms and neural mechanisms. The authors interpreted these outcomes as indicative of reduced activity in the premotor cortex, possibly attributable to disuse, neural atrophy, and colonization (Arrighi et al., 2011; Freund et al., 2011). Conversely, in 2003, Pavlova et al. (Pavlova, 2003) investigated the visual processing of BM in adolescents who were born prematurely, both with and without brain injury, as well as in healthy term-born peers. Brain injury, specifically periventricular leukomalacia (PVL), refers to hypoxic-ischemic damage of periventricular white matter commonly observed in preterm infants, typically occurring early in the third trimester of gestation (Volpe, 1994). This type of lesion often involves damage to the cortico-spinal tract, primarily impacting motor function in the lower limbs (Bax et al., 2006) and, occasionally, to a lesser extent, in the upper limbs. Notably, PVL is considered a significant contributor to visual impairment in prematurely born children (Jacobson et al., 1996; Tinelli et al., 2020). Pavlova et al. (Pavlova, 2003) discovered that individuals with PVL exhibited reduced sensitivity to perceiving BM, such as a walking figure, compared to control groups comprising children with typical development and those born preterm without PVL. Interestingly, the authors noted no correlation between the perception of BM and motor abilities but found a notable correlation between perception and the extent of the lesion.

Exploring this context, in this study, we delved into the capacity of children with PVL to discriminate the size of an object through the observation of a point-light movie, considering the grasping action as either an allocentric or egocentric viewpoint. The chosen stimulus is robust, having been previously employed in studies involving adults (Campanella et al., 2011), typical children (Tinelli et al., 2017) and children with neurodevelopmental disorders (Turi et al., 2017). The choice of this specific population, in line with the studies of Pavlova (Pavlova, 2003; Pavlova et al., 2001; Pavlova et al., 2006), regards the possibility of investigating mechanisms underlining BM perception, thanks to a pediatric population that differs from typical developing children for several reasons. Indeed, children with PVL show not only early brain lesions that might provoke a different cerebral organization of BM networks but also

experience differently observed and acted grasping from the first periods of life. This is because early neuromotor and neurovisual impairment, reducing the possibility of efficiently organizing finalized movements, negatively impacts several domains of development and, consequently, reduces the opportunity to learn from early psychomotor experiences in the environment (Hadders-Algra, 2001). Based on these points, the objective of our study is to untangle the extent to which motor impairment and/or visual perceptual impairment may impact performance in this task.

## 2. Material and methods

### 2.1. Participants

The research involved the inclusion of patients referred to the Division of Child Neurology and Psychiatry at the University of Pisa and IRCCS Stella Maris Scientific Institute of Pisa. The PVL group comprised 22 patients (mean age: 10.7, SD: 2.8 years, range 7–19; 15 males). The selection criteria were as follows: (1) evident indications of PVL detected through MRI; (2) confirmation of bilateral cerebral palsy through neurological examination, classified using the Gross Motor Function Classification System (GMFCS) (Palisano et al., 1997) and the Manual Ability Classification System (MACS) (Eliasson et al., 2006); (3) normal verbal Intelligence Quotient levels ( $VIQ \geq 70$ ); (4) the absence of significant eye abnormalities such as cataracts and optic atrophy; (5) binocular visual acuity above 7/10 (near and far), evaluated with corrective lenses if needed (see Table 1). Gross-motor impairment was categorized based on the Gross Motor Function Classification System (GMFCS) (Palisano et al., 1997) into five motor levels: Level I) walks without restrictions, with limitations in more advanced gross motor skills; Level II) walks without an assistive device, with limitations in walking outdoors and in the community; Level III) walks with an assistive mobility device, with limitations in walking outdoors and in the community; Level IV) self-mobility with constraints; children are transported or use power mobility devices outdoors and in the community; Level V) self-mobility is severely limited despite the use of assistive technology. In a parallel manner, the manual ability was classified according to the Manual Ability Classification System (MACS) (Eliasson et al., 2006) into five levels: Level I) manipulates objects easily and successfully; Level II) manipulates most objects but with somewhat reduced quality and/or speed of accomplishment; Level III) manipulates objects with difficulty, requiring assistance to prepare and/or modify activities; Level IV) manipulates a limited selection of easily managed objects in adapted situations; Level V) does not manipulate objects and has severely limited ability to perform even simple actions.

In a subset of patients ( $n = 16$ ), we measured coherence thresholds for form and motion using the stimuli and procedures outlined by Gunn et al. in 2002 (Gunn et al., 2002), providing an indicator of visual processing in the ventral and dorsal streams. Both these tasks require the integration of local visual signals to extract a global pattern and also permit the measurement of the ability to detect form and motion perceptually. Normative data from form and motion coherence tasks were employed to assess the performance of PVL children (Gunn et al., 2002).

Furthermore, 17 typically developing children (mean age: 11.8 years, SD: 2.6, range: 9–17, 12 males) were included. The groups were matched in terms of chronological age ( $t(37) = 1.42, p = 0.16$ ) and verbal-scale IQ ( $t(37) = 1.53, p = 0.13$ ), as assessed by the Wechsler Intelligence Scale for Children, Fourth Edition (O'Donnell, 2009); refer to Table 1 for specifics. All typically developing children reported no history of medical or developmental disorders, and their parents confirmed the absence of any current or past medical or psychiatric diagnoses. Every participant underwent individual testing in a serene environment, either within their residence or at IRCCS Stella Maris Scientific Institute. Both the participants and their parents provided informed consent to partake in the study, which received approval from the regional paediatrics ethics committee at Azienda Ospedaliera-Universitaria Meyer.

**Table 1**

Demographic Information. Descriptive statistics for developmental variables for children with PVL and typically developing children. VIQ = Verbal Intelligence Quotient; GMFCS = Gross Motor Function Classification System.; MACS = Manual Ability Classification System.

	PVL	Control	Comparison
Gender (Male: Female)	15:7	12:5	$\chi^2_{(39)} = 0.02, p = 0.87$
Age (years)			
Mean (SD)	10.58 (2.7)	11.81 (2.6)	$t_{(37)} = 1.42, p = 0.16$
Range	7–17	9–17	
VIQ			
Mean (SD)	94 (14.47)	100.2 (9.06)	$t_{(37)} = 1.53, p = 0.13$
Range	70–129	85–111	
Weight at birth (gr)		–	–
Mean (SD)	1459.71 (442.66)		
Range	750–2250		
Gestational Age (months)		–	–
Mean (SD)	30 (3.06)		
Range	24–35		
GMFCS		–	–
Mean (SD)	2.59 (1.25)		
Range	1–5		
MACS			
Mean (SD)	1.68 (0.71)		
Range	1–3		

## 2.2. Procedures and Stimuli

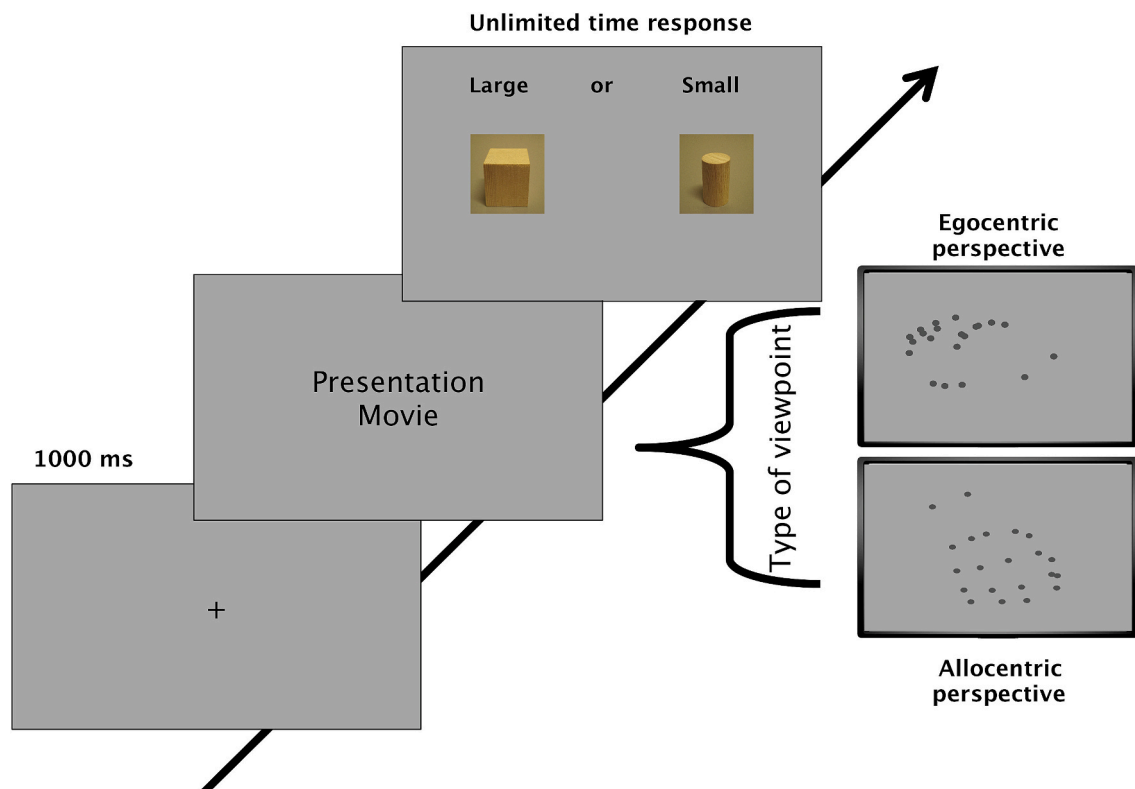
### 2.2.1. General procedures

A multidisciplinary team at IRCCS Stella Maris Foundation, a tertiary hospital for Childhood and Adolescent Neuropsychiatry in Pisa (Italy), diagnosed and evaluated children with PVL. In this context, specialized developmental therapists, psychologists and neurologists carried out functional evaluations of children's cognitive (IQ), motor (GMFCS and MACS) and neurovisual (basic and high-level visual functions) profiles. The second step was the administration of BM tasks to children who respected the inclusion criteria at the Vision Lab of the same hospital. Parallely, a team of psychologists administered cognitive tests and BM tasks to control children's groups from schools of the same regional zone. The administration of BM tasks had a duration of about 15–20 min. In 6 children with PVL, visual-perceptual tasks were not administered due to extreme tiredness or for lack of collaboration.

### 2.2.2. Biological motion stimuli

The visual stimuli employed in the study consisted of point-light BM movies illustrating a hand grasping two undisclosed objects (see online movies). These dynamic stimuli portrayed the identical hand movement from both an egocentric viewpoint and an allocentric perspective, as depicted in Fig. 1. The preparation of these BM stimuli was conducted beforehand (Campanella et al., 2011). During the preparation, actors were recorded executing a grasping motion on a cube or a cylinder using a set of cameras strategically positioned to capture the three-dimensional action. Twenty-three markers were placed on various points, including the centre of the nails, joints of all digits, the dorsal aspect of the hand, and the radial and ulnar styloid process. To manipulate the perspective of the grasping movement, the three-dimensional motion underwent a 180° rotation around the azimuth, ensuring that the visual information presented in the allocentric and egocentric views remained identical. The movie depicted both a lateral view and a top view of the hand grasping the objects. The cube had sides measuring 6.5 cm, while the cylinder stood 6.5 cm high and 4 cm wide. The motion consistently appeared in the centre of the screen, commencing either from the bottom or the top of the display for the egocentric and allocentric perspectives, respectively. To record hand trajectory during each reach-and-grasp movement, we used a near-infrared camera motion capture system (frame rate 100 Hz, Vicon; Oxford Metrics, Oxford, UK).

In our examination, we opted for two objects differing in size and shape—a large cube and a small cylinder. The objective was for children to determine which object had a greater size. This selection was informed by prior research undertaken by Campanella et al. (Campanella et al., 2011), where multiple control experiments elucidated that specific factors like maximum grip aperture, peak



**Fig. 1.** Examples of stimuli and procedures used in the experiment. Object identification task: biological motion movies representing hand-grasping non-visible objects of different sizes and shapes were displayed either from an egocentric (observing self-action, top example) or an allocentric (observing others' action, bottom example) point of view. Subjects were asked to indicate whether the goal of the reach-and-grasp movement was towards a small cylinder or large cube.

velocity of finger aperture, and percentage of time to maximal finger aperture were not employed by observers to differentiate objects of similar sizes. Discrimination based on shape, whether in the comparison of two diminutive objects or two substantial ones, did not surpass chance levels. Our instructions to participants emphasized discerning the size of the object without regard to its shape. The computer screen portrayed the biological motion of the hand movement, with the hand identified by black dots, utilizing the MATLAB Psychophysics toolbox (Brainard, 1997). The visual angle covered by the hand was approximately  $13 \times 15^\circ$  (for additional details, refer to the electronic supplementary materials of (Campanella et al., 2011)).

To estimate coherence thresholds, an up-and-down staircase method was utilized. In both tasks, 2 to 6 trials were presented with the initial coherence level set at 100 %. In subsequent trials, coherence was systematically decreased by one step until the first error, which formed the starting point for four reversals. The threshold was calculated as the mean coherence level during the last four reversals.

### 2.2.3. Procedures of administration of biological motion tasks

The visual stimuli were presented in a dimly lit room using a 15.4-in. Acer monitor with a resolution of  $1024 \times 768$  and a refresh rate of 60 Hz. The mean luminance of the screen was set to 60 cd/m<sup>2</sup>, and the stimuli were viewed binocularly from a distance of 57 cm. Each visual stimulus was displayed for a duration of  $0.90s \pm 0.15 s$ . Following the presentation of the movies, a response page appeared on the screen, and the subjects were instructed to indicate the object that was the target of the reach-and-grasp movement by pointing to it. Before data acquisition, each subject completed 5 training trials to familiarize themselves with the task. Subsequently, they performed 50 trials per block, with the order of starting conditions (egocentric or allocentric) pseudorandomized across subjects (eg. ABBA), ensuring a balanced order of conditions across subjects to mitigate order effects. No feedback was provided during the task, and there was no time limit for responding. Throughout the experiment, experimenters closely monitored the subjects' gaze to ensure that they were fixating on the centre of the screen. To prevent the discrimination task from being based on the movement trajectory, approximately an equal number of trials displayed grasping from the side and from above (with a difference of less than 10 % between the two conditions). To guarantee the clarity of task instructions for the children, the operator commenced by demonstrating a reaching and grasping movement towards both the cube and the cylinder, highlighting the distinction in size between the two objects. Subsequently, the subjects were prompted to replicate the same action. The operator only proceeded with the trial collection once it became apparent that the children had comprehended the task.

### 2.2.4. Visual perceptual tasks

The Form and Motion Coherence tasks are utilized to evaluate the integrity of the visual ventral and dorsal streams. The form stimulus comprises a static array of randomly oriented short-line segments, with a target area on one side displaying segments oriented tangentially to create concentric circles. Conversely, the motion stimulus consists of two random dot kinematograms, one of which is divided into three horizontal strips. The coherent motion direction of the middle target strip is opposite to that of the two outer strips.

Two alternative forced-choice paradigms were employed to measure coherence thresholds. In these paradigms, participants had to locate the target presented either to the right or left of the screen centre. In the Form Coherence Test, the subject had to recognize the ball in the middle of the grass. In the Motion Coherence Test, the subject had to find the road in the middle of the snow. For further details, see Gunn et al. (Gunn et al., 2002).

To estimate coherence thresholds, an up-and-down staircase method was utilized. In both tasks, 2 to 6 trials were presented with the initial coherence level set at 100 %. In subsequent trials, coherence was systematically decreased by one step until the first error, which formed the starting point for four reversals. The threshold was calculated as the mean coherence level during the last four reversals.

## 2.3. Data analysis

Statistical analyses were performed in Statistical Packages for Social Sciences (SPSS, Version 22, IBM Corp., Armonk, NY, USA). For the BM tasks, discrimination performance was assessed using the discrimination index  $d'$ , which was calculated as the difference between the z-scores of the hits and the false alarms. In a two-alternative forced-choice design, a  $d'$  value of 1 corresponds to approximately 76 % correct responses (threshold value), while a  $d'$  value of 0 corresponds to chance level or 50 % correct responses. To examine differences in sensitivity across conditions and between groups, as well as any potential interaction between them, we conducted a mixed repeated-measures ANOVA.

For the Form and Motion Coherence Tests, z-scores were calculated as:

$$\left( \frac{\text{patient's threshold} - \text{mean value of threshold for the age}}{\text{standard deviation for age}} \right)$$

using normative data reported in literature (Gunn et al., 2002).

Successively, we conducted correlation analyses to investigate the relationship between sensitivity measures of BM and clinical variables (age, gestational age, weight at birth). Moreover, correlation analyses between GMFCS and MACS levels and sensitivity measurements of BM were carried out. These analyses aimed to determine the association between motor impairments and task performance. Furthermore, bivariate correlations were used to examine the relationships between sensitivity measurements of BM and visual-perceptual tasks (z-scores from form and motion coherence threshold).

### 3. Results

Discrimination performance was measured by calculating the discrimination index  $d'$  for each group in both viewing perspectives. Fig. 2 displays the average  $d'$  values for the egocentric and allocentric conditions for both the PVL and control children's groups. To analyze these results, a mixed-design ANOVA was conducted, with perspective (egocentric, allocentric) as the repeated-measures factor and group (PVL and Control) as the between-participants factor. The analysis revealed a significant main effect of perspective ( $F_{(1,37)} = 14.80, p < 0.001, \eta_p^2 = 0.075$ ), indicating that performance differed between the two viewing perspectives. Specifically, participants exhibited better performance when stimuli were presented in the egocentric view (M: 1.07, SEM: 0.08) compared to the allocentric view (M: 0.75, SEM: 0.07).

Significant differences were also observed in terms of group effect ( $F_{(1,37)} = 17.98, p < 0.0001, \eta_p^2 = 0.24$ ). PVL children demonstrated lower sensitivity compared to control children in both the egocentric view (PVL: M = 0.77, SD = 0.51; Control: M = 1.36, SD = 0.49;  $t_{(37)} = 3.56, p = 0.001$ ) and the allocentric view (PVL: M = 0.48, SD = 0.53; Control: M = 1.02, SD = 0.31;  $t_{(37)} = 3.68, p = 0.001$ ). However, no statistically significant interaction was found between perspective and group ( $F_{(1,37)} = 0.05, p = 0.81, \eta_p^2 < 0.0001$ ). It is noteworthy that both groups, consistent with previous findings (Campanella et al., 2011; Turi et al., 2017), exhibited higher sensitivity in the egocentric view compared to the allocentric view (Control:  $t_{(16)} = 2.90, p = 0.01$ , PVL:  $t_{(21)} = 2.61, p = 0.01$ ).

To further investigate the size discrimination based on grasping configuration, we conducted a mixed-design ANOVA on the discrimination index  $d'$ . The group served as the between-participants factor, and the grasping configuration (Side and Above) as the within-participants factor. As depicted in Fig. 2B, the analysis revealed a significant main effect of group ( $F_{(1,37)} = 16.89, p < 0.001, \eta_p^2 = 0.31$ ), indicating superior overall size discrimination in the control group (Control: M = 1.16, SEM = 0.1) compared to the PVL group (M = 0.59, SEM = 0.1). PVL children exhibited reduced sensitivity compared to control children in both side view ( $t_{(37)} = 3.06, p = 0.004$ ) and above view ( $t_{(37)} = 3.79, p = 0.001$ ). However, no statistically significant main effect of grasping configuration was observed ( $F_{(1,37)} = 0.92, p = 0.34, \eta_p^2 = 0.02$ ), and there was no significant interaction between grasping configuration and group ( $F_{(1,37)} = 0.38, p = 0.54, \eta_p^2 = 0.01$ ).

Regarding the Form and Motion Coherence Tests, PVL children showed mean z-scores that indicated a global impairment of both measures compared with normative data (Form Coherence M: -2.47, SEM: 0.74; Motion Coherence M: -0.34, SEM: 0.54).

To investigate the relationship between discrimination performance and age in both groups for the two perspectives, we conducted correlation analyses (see Fig. 3). In the control group, a strong and significant correlation was found between performance and age for the egocentric perspective ( $r = 0.87, p < 0.0001$ ), indicating that as age increased, discrimination performance improved. However, there was no significant correlation between performance and age for the allocentric perspective ( $r = 0.38, p = 0.11$ ).

Similarly, in the PVL group, a significant correlation was observed between performance and age for the egocentric perspective ( $r = 0.48, p = 0.02$ ), indicating that as age increased, discrimination performance improved to some extent. However, no significant correlation was found between performance and age for the allocentric perspective ( $r = 0.04, p = 0.86$ ), suggesting that age did not have a significant impact on discrimination performance in this perspective for the PVL group.

To explore any potential causal relationship between size discrimination impairment and motor impairments or clinical variables,

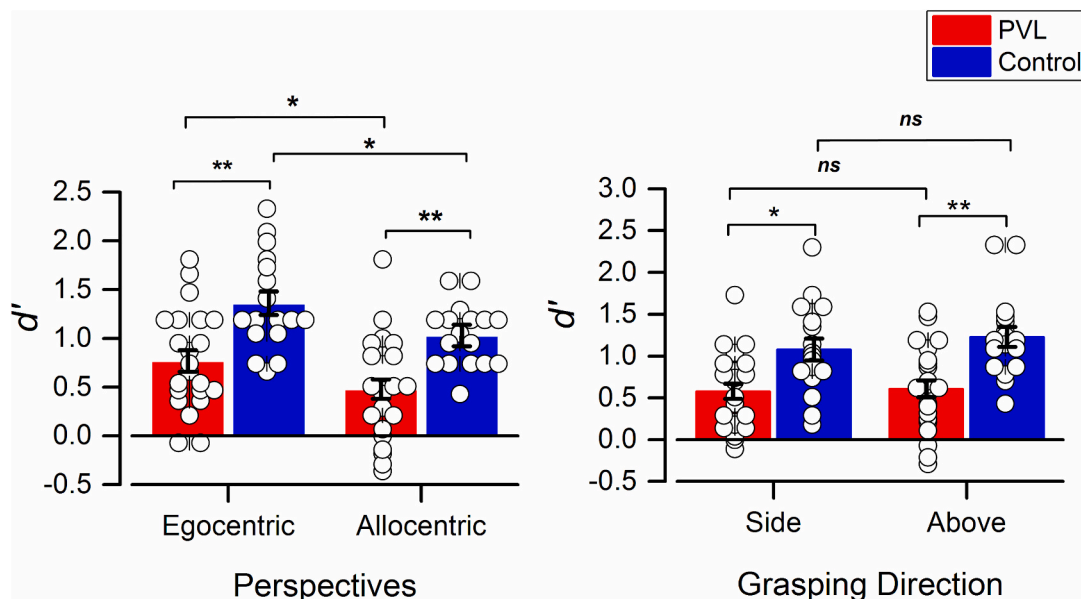
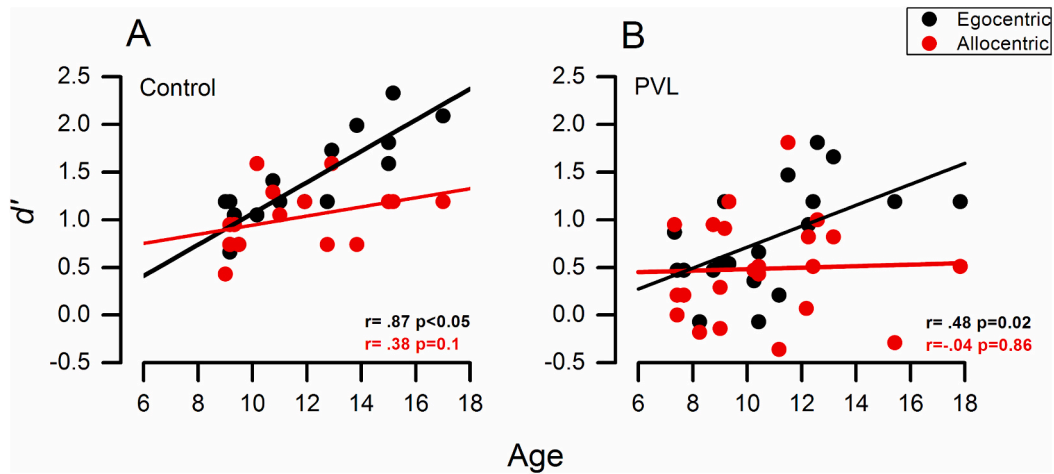


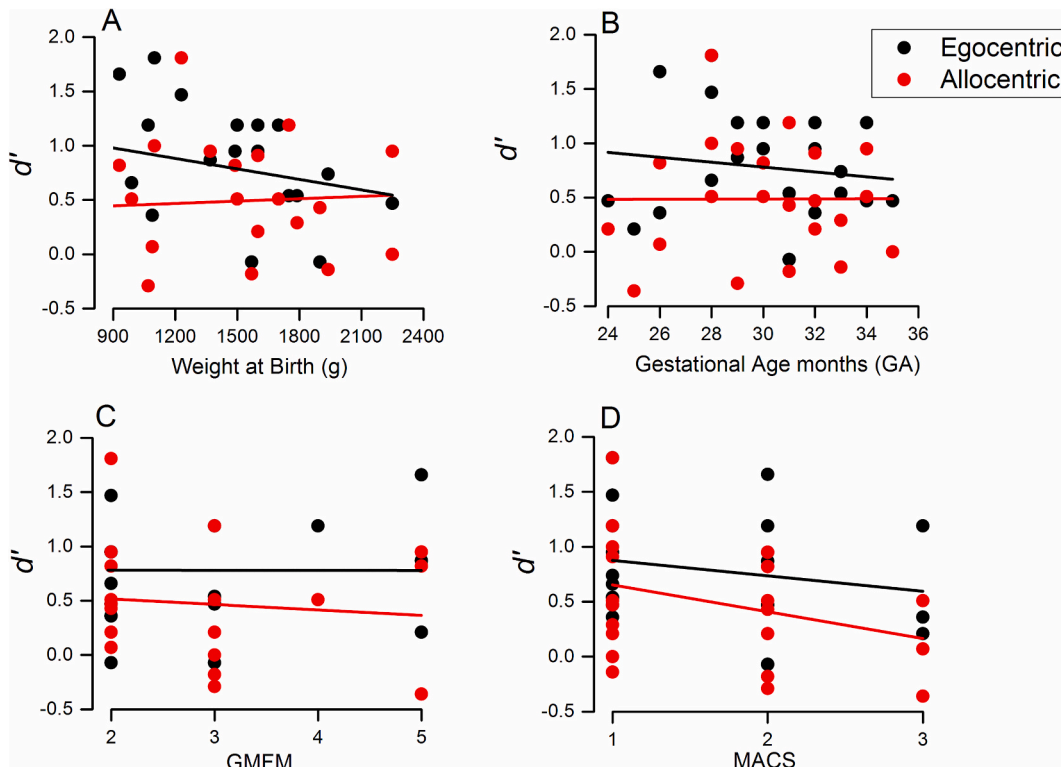
Fig. 2. Group differences in discriminating objects. A) Mean discrimination performance ( $d'$ ) in the egocentric and allocentric conditions for the two groups. B) Mean discrimination performance ( $d'$ ) as a function of grasping configuration (Side or Above) for the two groups. Error bars correspond to  $\pm 1$  SEM. Stars refer to the significance of  $p$  values: \*\*\* $p < 0.001$ , \*\* $p < 0.01$ , \* $p < 0.05$  and ns non-significant.



**Fig. 3.** Relationship between discrimination and age across the groups. Discrimination performance ( $d'$ ) as a function of age (Egocentric view: black; Allocentric view: red). The color-coded lines show the correlation within each perspective. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

we analyzed the relationship between discrimination performance and measures of weight at birth and gestational age. Fig. 4 illustrates that there were no significant correlations between size discrimination in the allocentric and egocentric conditions and any of our clinical variables (all  $p > 0.05$ ). These results indicate that these specific clinical variables did not influence the discrimination performance in the studied sample.

Finally, as shown in Fig. 5 in a subsample of PVL children ( $n = 16$ ), in which we measured form and motion coherence threshold, a statistically significant correlation was found between form coherence z-score and size discrimination in egocentric view ( $r = 0.54, p =$



**Fig. 4.** Relationship between discrimination, lesion severity and clinical variables. Discrimination performance ( $d'$ ) as a function of: A) Weight at Birth, B) Gestational Age, C) Gross Motor Function (GMFM), D) Manual Ability Classification System (MACS) for all PVL children (Egocentric view: black; Allocentric view: red). The color-coded lines show the correlation within each perspective. All correlations were not statistically significant. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

0.028). In contrast, a nearly statistically significant trend was found with size discrimination in allocentric view ( $r = 0.49, p = 0.052$ ). No statistically significant correlation was found between motion coherence z-scores and the size discrimination in both views (all  $p > 0.05$ ). In addition, we found that form and motion coherence are not statistically correlated ( $p > 0.05$ ), probably tapping different aspects of visual processing.

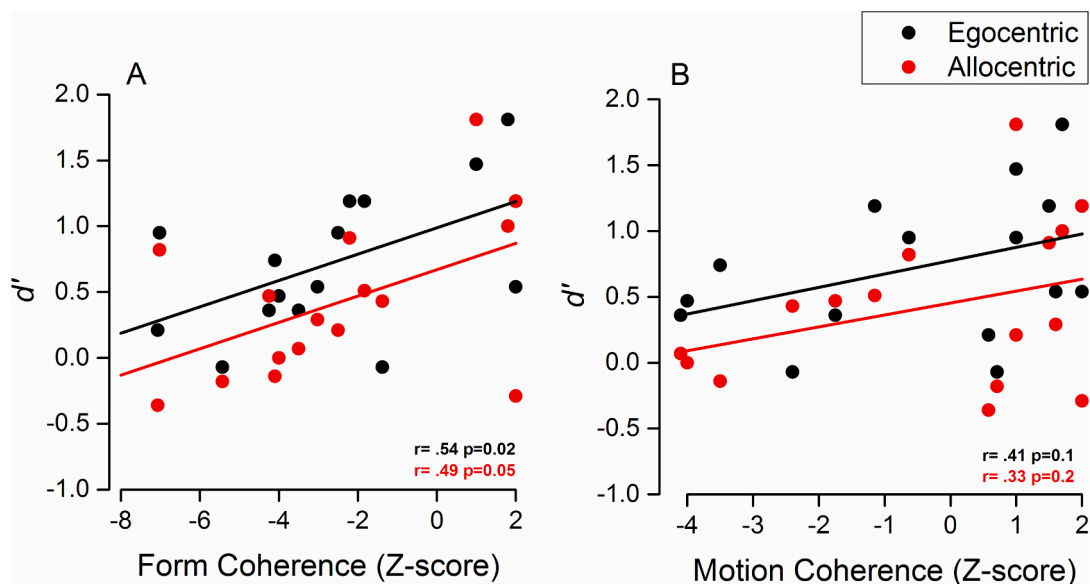
#### 4. Discussion

This research sought to delve into the proficiency of children affected by periventricular leukomalacia (PVL) and bilateral cerebral palsy in discerning the size of an unseen object based on a seen hand movement. This inquiry involved the examination of a point-light movie depicting an actor's grasping action towards the object, presented from either an allocentric or egocentric viewpoint (observing others or oneself). The overarching goal was to unravel the extent to which this ability is shaped by motor processes and/or high-level visual-perceptual mechanisms. Individuals with PVL experience challenges in motor functioning, particularly affecting the lower limbs and often extending to the upper limbs. Additionally, they encounter high-level visual impairment, particularly in discriminating motion (MacKay et al., 2005; Merabet & Pascual-Leone, 2010; Morrone et al., 2008; Ruby & Decety, 2001; Taylor et al., 2009).

In this study, we demonstrate a notable impairment in their ability to perceive BM during grasping actions. Intriguingly, these individuals maintain the capacity for improvement when observing from an egocentric viewpoint, akin to the pattern observed in individuals without neurological conditions. Despite all participants exhibiting heightened sensitivity in the egocentric view relative to the allocentric perspective, children with PVL displayed lower performance scores compared to their typically developing counterparts in both observational viewpoints. As highlighted in a prior publication (Arrighi et al., 2011), distinct cerebral areas and circuitry are activated by allocentric and egocentric perspectives, potentially undergoing diverse maturation processes. Similarly, Ruby and Decety (Ruby & Decety, 2001) showed that during a task of mental simulation of action, different brain regions are activated depending on whether the participant imagines manipulating an object themselves or imagines someone else doing it. In the first case, regions in the left hemisphere are activated, including the inferior parietal lobe, precentral gyrus, superior frontal gyrus, occipito-temporal junction, anterior insula, and ipsilateral cerebellum. In the case of third-person object manipulation, the right hemisphere is engaged, specifically involving the inferior parietal cortex, precuneus, posterior cingulate, and frontopolar cortex.

Moreover, our results indicate that only sensitivity to the egocentric view increases with age, consistent with previous findings in typically developing children, in which the sensitivity for the egocentric perspective gradually becomes greater than for the allocentric perspective after 9 years of age (Tinelli et al., 2017). This underscores the notion of a different maturation process in cortical areas governing the allocentric viewpoint that is more implicated in real-life scenarios involving the imitation of others' actions for social learning and knowledge acquisition than in the control of fine motor dexterity. Indeed, the perception of the movement of grasping from an egocentric perspective seems to excel from 9 years of age, which is the time window when hand motor representation areas and manual dexterity improve in humans (Säisänen et al., 2021).

Despite significant motor deficits, children with PVL exhibit an enhanced ability to discriminate the goal of grasping actions from an egocentric perspective rather than an allocentric perspective. This suggests that the BM perception in an allocentric perspective



**Fig. 5.** Relationship between discrimination and Form and Motion coherence threshold. Discrimination performance ( $d'$ ) as a function of: A) Form Coherence Threshold, B) Motion Coherence Threshold for a subsample ( $n = 16$ ) of PVL children (Egocentric view: black; Allocentric view: red). The color-coded lines show the correlation within each perspective. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



might not be intricately tied to the development of fine motor control, while the progressive experiences in the first person of grasping and manipulation of objects could be an important aspect for the maturation of scores in the egocentric perspective.

In fact, the continuous experience of successfully predicting the action goal and its consequences during daily life may not be directly associated with motor signals but with error signals computed at the cognitive level that develop with age and with similar developmental courses in PVL and typical children.

Despite the impairment found in the allocentric versus egocentric perspective being similar in PVL and controls, it remains to be understood why the performance of participants with PVL is so markedly impaired compared to controls.

In our study, we also aimed to investigate the nature of this deficit, taking into consideration different variables: in particular, the age of children was considered a proxy for the amount of experience and level of maturation, while GMFCS was used as an index of global motor impairment, MACS as an index of grasping proficiency, and finally, the Form and Motion Coherence Tests as indexes of a high-level visual impairment.

Similarly to our result, Pavlova and colleagues, using the typical runner stimulus, found a specific impairment in BM discrimination and no correlation with motor impairment was evident (Pavlova et al., 2006). Likewise, we also analyzed the possible correlation with GMFM and MACS, but no correlation was found. So, both studies strongly demonstrate that the capacity of the brain to detect BM may be substantially impaired by periventricular lesions, even if they occur very early in life, but this does not seem to be linked to the level of motor skill proficiency.

Thus, the last hypothesis regards the possibility that the higher visual processes that mediate object size discrimination may contribute to the different development of BM perception in PVL children.

It is widely demonstrated that BM perception hinges on specific cortical areas along the superior temporal sulcus (STS) (Neri et al., 1998). Individuals with normal sensitivity to motion speed, direction, and pattern may still struggle to perceive BM (Schenk, 1997). Surprisingly, even patients with bilateral lesions along the dorsal pathway, rendering them nearly or entirely “motion-blind” due to impaired visual motion perception, can consistently recognize human actions in point-light displays. Equally unexpected, individuals with visual agnosia resulting from bilateral ventral lesions encompassing the posterior temporal lobes can effortlessly and accurately identify BM. Based on these findings, Vaina et al. (Vaina, 1994) proposed the hypothesis that while motion stimuli primarily activate the dorsal system and form and face stimuli activate the ventral system, the recognition of BM stimuli may engage both systems. Therefore, brain damage affecting regions at the confluence of the ventral and dorsal visual streams, particularly the STS, could account for deficits in BM perception.

We found a significant correlation between form perception and BM perception, while no correlation was found between motion discrimination and BM perception. This is in line with a study by Miller et al. (Miller et al., 2018) that found no relationship between global motion perception and performance in any of the three BM conditions they tested, which indicates that the neural mechanisms underlying the processing of these two tasks do not entirely overlap. On the contrary, the correlation between BM perception and form coherence perception could be linked to the fact that the ability to recognize coherent shapes or patterns may engage more fundamental visual processing mechanisms that are independent of perspective. This also could explain why, in our study, both perspectives exhibit a similar positive relation with form coherence perception. However, with the allocentric view, there was only a significant trend of correlation, while with the egocentric perspective, the correlation with the form perception was stronger. This again reinforces the suggestion that the improvement in the egocentric view may be related to the increased ability of size and shape perception and not to the motor system per se. These findings also suggest that a dysfunction of the ventral stream, related to form perception and discrimination, might cause the atypical development of BM perception in children with PVL. This is in line with the data of Wittinghofer et al. (Wittinghofer et al., 2012), who highlighted that object recognition and biological motion perception share capacities and, therefore, that biological motion recognition can be seen as a special case of object perception. Additionally, Beintema and Lappe (Beintema & Lappe, 2002) disrupted local motion information in BM walkers, preserving their global form, showing that BM can be discriminated by form information alone.

As well described by Guzzetta and colleagues (Guzzetta et al., 2009), specific difficulties in visual processing are present in children born preterm in the presence or absence of brain lesions: in particular, in the absence of brain lesions, the preterm child’s difficulties seem to concern specifically the functions linked to the dorsal pathway (occipito-parietal) while, in the presence of PVL, it is possible to find more generalized visual-perceptual difficulties, with involvement of both the dorsal pathway (occipito-parietal) and the ventral pathway (occipito-temporal). This interpretation is corroborated by our results. Moreover, also Fazzi and collaborators (Fazzi et al., 2009) described patterns of ventral and dorsal stream malfunctioning in children with PVL, suggesting a more widespread impairment of higher visual processing involving both the ventral and dorsal visual systems and supporting the idea of deep integration between the two pathways.

In conclusion, in this study, we show that perception of BM is impaired in PVL children, similarly to other perceptual functions. Our findings, together with previous studies, show a great involvement of the visual system in individuals with congenital brain lesions. This contrasts with the strong and selective visual motion deficit observed in subjects with acquired motor impairment in adulthood. Indeed, patients with motor impairment due to premotor cortical dysfunction reduced in long-term paraplegia show reduced sensitivity to biological motion (Arrighi et al., 2011), suggesting a pivotal role of action execution in modulating the visual system. The difference between the two groups may result from the capability of a developing brain to partially compensate for the lack of appropriate motor signals. However, further study needs to be completed to address this important point.

#### CRedit authorship contribution statement

**Francesca Tinelli:** Writing – original draft, Methodology, Data curation, Conceptualization. **Giulia Purpura:** Writing – original

draft, Investigation, Data curation. **Giovanni Cioni:** Supervision, Conceptualization. **Maria Concetta Morrone:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Marco Turi:** Writing – review & editing, Methodology, Formal analysis, Conceptualization.

## Declaration of competing interest

The authors report there are no competing interests to declare.

## Data availability

Data will be made available on request.

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