Applicability of computerised motion perception tasks in clinical practice for children. A systematic review

ABSTRACT

Problem

A variety of computerised tasks is being used in research to assess motion perception in children. Which can be applied in clinical diagnostics?

Methods

Published studies in children aged 2-12 years were systematically reviewed to judge 1. types of tasks, technical specifications and quantitative outcomes; 2. reliability of normal limits and developmental trends; 3. differences between typically developing children and risk groups (mean performance and percentage abnormal performers).

Key findings

Global motion has been studied most extensively, whereas a smaller number of studies focussed on motion-defined form and biological motion. There was a wide variety in task characteristics, and confidence intervals for normal limits were wide as a result of small age groups. Developmental trends were observed for global motion and motion-defined form. Several risk groups performed significantly worse than typically developing children, but taking confidence intervals into account, there is only some evidence for an increased risk of abnormal performance in children with autism, amblyopia, and prematurely born children.

Interpretation

Computerised motion perception tasks can be used in clinical practice as observational instruments with quantifiable outcomes, but because of unreliable normal limits, abnormal performers cannot yet be identified reliably. International collaboration might be needed to study larger patient groups in order to estimate the prevalence of motion perception problems.

INTRODUCTION

Motion perception is the specific mental function of recognizing and interpreting dynamic visual information. Motion perception can be selectively impaired following damage to the lateral occipital-temporal cortex, although it seems never completely absent.[1] Acquired lesions in adults illustrate the importance of motion perception in daily activities.[2]

Various aspects of motion perception can be distinguished, e.g. the perception of coherent or global motion, biological motion, and motion-defined form.

Motion perception deficits are associated with various developmental disorders, e.g. Williams syndrome (WS), autism, hemiplegia and developmental dyslexia.[3] However, the computerised motion perception tasks used in these studies are still uncommon in clinical practice. In Dutch low vision centres, motion perception is assessed occasionally by means of observational methods, e.g. observing the reaction of a child to an approaching rolling ball. The advantage of motion perception tasks is that they have a quantitative outcome measure, i.e. a perception threshold, that allows to diagnose the presence and severity of a motion perception impairment.[4, 5] Early detection of motion perception impairment is preferred to allow early intervention. Therefore, making such tasks available to the clinic is of great advantage.

A wide range of computerized motion perception tasks used in scientific studies address different aspects of motion perception in different ways. As a result, it remains unclear which of the currently available tasks can be introduced in low vision centres for clinical diagnostic purposes.

Therefore, we performed a systematic review of the literature in order to: (1) provide an overview of the types and characteristics of motion perception tasks used in children, with their main technical specifications and quantitative outcome measures (thresholds); (2) evaluate current knowledge on normal limits, their precision, and developmental trends; (3) give an overview of validation studies, which show differences between patient groups and typically developing children, i.e., the evidence for motion perception impairment of different kinds in paediatric populations. Based on the results, we will discuss which of the available tasks have the best characteristics and could be introduced safely as a diagnostic test in low vision centres. In this review we focus on both preschool and school-aged children (age between 2 and 13 years), because most motion perception tasks require understanding of task instructions and at least some cooperation of the child.

METHODS

Literature search

We searched for English-language articles and reviews on motion perception, published until March, 2009, using several public databases. In ISI Web of Knowledge we searched in all citation databases, setting the time span at all years. In PubMed we only used a search string without additional limits. For the search in Embase, the databases EMbase and Unique MEDLINE were selected. A fourth and last search was done in PsycInfo. Search strings and numbers of hits are shown in Table 1.

Table 1. Search strings used in each database and number of hits.

Database	Search string	Hits
ISI Web of Knowledge	TS = (motion perception) AND TS = ("motion coherence" OR "global motion" OR "motion direction" OR "biological motion" OR "form from motion" OR "motion defined form") AND TS = (children) NOT TS=(infants) AND Language=(English) AND Document Type=(Article OR Review) Databases=SCI-EXPANDED, SSCI, A&HCI Timespan=All Years	59
PubMed	(("Child, Preschool"[Mesh] OR "Child"[Mesh])) AND ("motion perception"[MESH] AND ("biological motion"[Title/Abstract] OR "motion coherence"[Title/Abstract] OR "global motion"[Title/Abstract] OR "motion direction"[Title/Abstract] OR "form from motion"[Title/Abstract] OR "motion defined form" [Title/Abstract])) AND (("Child, Preschool"[Mesh] OR "Child"[Mesh])) AND ("motion perception"[MESH] AND ("biological motion"[Title/Abstract] OR "motion coherence"[Title/Abstract] OR "coherent motion"[Title/Abstract] OR "global motion"[Title/Abstract] OR "motion direction"[Title/Abstract] OR "form from motion"[Title/Abstract] OR "motion defined form" [Title/Abstract]))	42
Embase	('movement perception'/exp/mj OR 'movement perception') AND ([article]/lim OR [review]/lim) AND ([preschool]/lim OR [school]/lim) AND ('biological motion' OR 'motion coherence' OR 'global motion' OR 'motion direction' OR 'form from motion' OR 'motion defined form')	16
PsycInfo	(Motion perception and ("biological motion" or "motion coherence" or "global motion" or "motion direction" or "form from motion" or "motion defined form")).mp. limit to (all journals and (160 preschool age <age 2 to 5 yrs> or 180 school age <age 6 to 12 yrs>))	30

Eligibility of studies

Based on the abstracts, or if needed the complete article, two authors independently judged the articles using the following inclusion criteria: original article published in English; subgroups of participants containing at least 5 participants; children aged 2 to 12 years included in the study; typically developing children and/or patients studied; if patients were studied, at least a typically developing control group had to be included too; motion perception, specified as either motion coherence/global motion, motion defined form, or biological motion was tested; biological motion tasks used stimuli expressing global motion of the whole human body; quantitative outcomes, other than quality judgements of the imitation of presented motions, EEG and fMRI

results, were reported for the motion perception tasks; if typically developing children older than 12 years of age were also studied, quantitative data for a subgroup of children aged up to 12 years had to be extractable from the published results. If a group of patients including children with a chronological age above 12 years was matched by developmental age to a group of typically developing children, results of patients with a developmental age up to 12 years had to be extractable from the article. If one of the above criteria was not met, the article was excluded. We discussed all discrepancies in judgement, until consensus was reached on the eligibility of the study.

Data extraction and quality assessment

The following data were extracted: date of publication, authors, recruitment location for participants, and participant selection methods; type and number of participants; type of task and task characteristics; type of quantitative results and formulae used; methods of statistical analysis; group results, group differences and significance of differences.

Quality assessment, based on the Quality Assessment Tool for Quantitative Studies,[6] was done by two authors independently. Difficulties in data extraction and quality assessment were discussed, until consensus was reached.

For the evaluation of possible confounders, comparability of groups was assessed. In comparative studies (patients vs. controls), we focussed on age, visual acuity and social economical background (SES) or intelligence (IQ). In developmental studies (only typically developing children of different ages) we focussed on visual acuity and social economical background (SES) or intelligence (IQ). We considered SES and IQ as one variable, because SES and IQ are significantly related and SES seems to influence cognitive development in children.[7-9] In comparative studies, the confounding risk was rated 'low' if groups were comparable on all three variables or analysis had shown that confounding was not likely, 'moderate' if confounding was not likely for two, and 'high' if confounding was not likely for one variable. In developmental studies, the confounding risk was rated 'low' if studies were longitudinal and both variables were reported and controlled for; 'moderate' if studies were cross-sectional and both variables were reported and controlled for; and 'high' if one variable was reported and controlled for.

Bias was assessed by judging the recruitment setting, selection procedure and the level of participation (% agreement of invited persons). Because it appeared, that such information was absent or limited in all articles, whereas participant groups of all studies were too small to obtain reliable normal limits, we ignored bias risk in the analyses and do not present the rating here.

For the description of task characteristic and thresholds, all studies were included. We examined the following task characteristics: response by participant, stimulus type, motion direction per trial, dot speed and dot size, as well as task distance, monocular or binocular testing. For the evaluation of normal limits and differences between risk groups and typically developing children, we included studies with a low or moderate confounding risk.

Analysis

To study normal limits for the general population, we focussed on typically developing children. Normal limits or cut-off values are crucial for diagnostic use: a task performance outside the normal limits is labelled as abnormal or deviant. Sample limits were used to estimate normal limits. To estimate the precision of reported sample limits, we calculated the 95% confidence intervals (95%-CI) for the intended percentage excluded participants with the exact binomial method of Clopper-Pearson.[10, 11] This confidence interval indicates how many of the general population may be considered abnormal if the reported normal limits are used.

To study and illustrate developmental trends for mean performance and sample limits, we combined the data of typically developing children of different studies in a graph, provided that outcome measures were identical, and stimuli, responses and procedures were comparable, and drew a regression line. To compare sample limits of different studies, we estimated p90 (90^{th} percentile) for each sample, defined as 1.28 SD above the mean. We assumed that data were distributed normally and that the reported mean and SD were the true population values. The relation between age and outcome was studied with the Spearman rho correlation and we drew illustrative trend lines. Differences in performance on motion perception tasks between various patient groups and controls were studied in two ways.

First, we evaluated group differences in mean performance. If summary data, but no statistics were reported, group means were compared by means of a t-test, provided that groups were comparable.

Second, we evaluated differences in the percentages of abnormal performers. Only if the patient groups show a significantly higher frequency of abnormal performers, it is likely that patients have a higher risk of motion perception problems. To evaluate whether the percentage abnormal performers, observed in patients, was significantly higher than that observed in controls, a binomial proportion test for independent samples or Fisher's exact test was used. These tests were also used to evaluate whether more patients than controls would be labelled as abnormal, under the assumption that the upper limit of the

95%-CI of the intended percentage of excluded controls is the true population frequency of abnormally performing controls if the estimated normal limits are used. If this difference is significant, the patient group can be considered at risk if the normal limits are adjusted to reduce the number of abnormally performing controls in the general population.

To indicate the possible range of abnormally performing patients in the patient population given the sample limit estimated in the control group, we also calculated the 95%-CI of the percentage abnormally performing patients, as had been done for the controls.

Differences were considered significant at $p \leq .05$.

RESULTS

Study selection

Totally, 82 unique articles were found, of which 56 were excluded, some for multiple reasons (Table 2). The remaining 26 articles were included in the review, after discussion of six cases, primarily on the type of motion perception task and the extractability of data. Two tasks using global motion-like stimuli were not included, because they were based on motion discrimination, motion speed discrimination and motion direction discrimination,[12] and not on motion detection. In one article,[13] no data were extractable for one of two experiments on biological motion, therefore only one experiment was included. For five studies[12-16] also including children older than 12 years, data of patients with a chronological age over 12 years but a younger mental age were extracted, whereas for their control groups, only data of children with a chronological age under 12 years were used.

Table 2. Main reason for exclusion of the articles not included in this review

Reason for exclusion	# articles
Only abstract published	1
Qualitative review	7
Number of participants < 5	2
Age of participants outside range 2-12 years	18
Other task characteristics than specified for review	7
No quantitative outcome measures (fMRI, EEG, qualitative assessment motion imitation)	6
No quantitative data extractable for children in age range 2-13 years	14
Duplicate data	1
Total	56

Study characteristics and quality assessment

Table 3 presents the 26 included studies, the study design and the evaluation of confounding risk. All articles were published after 1994 and 22/26 focused on a single motion perception aspect. All studies, including six developmental studies, were cross-sectional. In only 6 articles, information on age as well as visual acuity and SES or IQ was given and sufficiently controlled for, resulting in a low confounding risk. Confounding risk was judged as moderate in 10 and high in another 10 studies.

Table 3. Rating of confounding risk

Task type	Year	Study	Design	Confounding risk rating
GM	1998	Raymond & Sorensen [17]	Comp	moderate
	2000	Spencer et al [18]	Comp	high
	2002	Gunn et al [19]	Comp	low
		O'Brien et al [20]	Comp	low
		Ellemberg et al [21]	Comp	high
	2003	Atkinson et al [22]	Comp	high
	2004	Ellemberg et al [23]	Dev_c	high
	2005	MacKay et al [24]	Comp	low
		Chow & Ho [25]	Comp	moderate
		Mendes et al [12]	Comp	moderate
	2006	Milne et al [26]	Comp	moderate
	2006	Del Viva et al [15]	Comp	moderate
	2008	Pellicano & Gibson [27]	Comp	low
GM & MDF	2005	Ho et al [28]	Comp	moderate
		Parrish et al [29]	Dev_c	high
	2007	Wang et al [30]	Comp	moderate
MDF	1992	Giaschi et al [31]	Comp	moderate
	1999	Schrauf et al [32]	Dev_c	high
	2006	Jakobson et al [33]	Comp	low
BM	1995	Moore et al [13]	Comp	moderate
	2001	Pavlova et al [34]	Dev_c	high
	2002	Jordan et al [16]	Comp	moderate
	2003	Blake et al [35]	Comp	high
	2006	Freire et al [36]	Dev_c	high
	2008	Lichtensteiger [37]	Dev_c	high
GM, MDF & BM	2005	Reiss et al [14]	Comp	low

GM = global motion or motion coherence, MDF = motion-defined form; BM = biological motion (including global human motion. Comp = comparative study, comparing patients with controls, Dev_c = cross-sectional developmental study, comparing different age groups of typically developing children.

Motion perception tasks and thresholds

In the 26 studies, a wide variety of tasks were applied (tables with detailed specification of threshold and response types, stimulus characteristics and test distance of all studies are presented in the Appendix 1). Global motion was studied most extensively, with motion coherence as the primary threshold. The most common threshold for motion-defined form was minimum dot speed and for biological motion an accuracy indicator. Most stimuli consisted of white dots on a black background, slowly moving dots and a dot size greater than 6 arcmin, which should be visible for people with a visual acuity of 0.17 or higher at test distance. Test distance varied between 40 centimetres and 6 metres. In 4 studies it was reported that testing was done binocularly[17, 23, 26, 32] and in 6 studies monocularly,[21, 24, 28-31] whereas this remained undefined in the other 16 studies. Apart from these aspects, tasks also differed in number of dots per random-dot kinematogram (RDK) or target, dot density range and size of targets. Additionally, studies differed by whether or not they controlled for undesirable effects, such as the use of local motion cues or tracking of a single dot. To prevent this effect, the lifetime of signal dots was limited in ten studies.[14, 15, 17, 19, 21-24, 26, 27] The range of signal dot lifetimes was 13.3 ms-120 ms.[19, 21, 22, 24, 26, 27] One of 17 global motion studies[21] controlled for possible bias as a result of horizontal nystagmus, which is associated with a reduced sensitivity for horizontal motion,[38] by presenting vertical motion.

Taking all task aspects into account, only two global motion studies with motion direction[28, 30] and two studies with target location as response[18, 20] used exactly the same task and task procedure. Additionally, three studies on motion-defined form used identical stimuli and thresholds and comparable task procedures.[28-30] Biological motion studies were not comparable.

Estimated normal limits

In 8 of 16 studies with a low and moderate confounding risk, some kind of sample limit or cut-off value was used (Table 4a-b).[17, 24, 26-28, 30, 31, 33] Sample limits were reported for global motion and motion-defined form tasks, but not for biological motion tasks.

In the second column of Table 4a-b, we summarize study characteristics (number of controls, mean age or age range of participants), formulas used to estimate sample limits and the cut-off values, the percentage of the normal population that authors were willing to label as abnormal and its 95%-CI as calculated by us. In 7 of 8 studies, a *z*-score or *SD* was used to estimate the sample limit, whereas the percentage intended to exclude in the general population ranged from 0.1 to 5% (M + 3 *SD* to M + 1.64 *SD*). This was often done

Table 4a. Estimated normal limits in global motion studies, the intended percentages of persons in the general population that are excluded by use of the estimated limit and labelled as abnormal performers, precision of sample limits (95%-CI), and percentages of abnormal performing patients according to the sample limits.

	Controls					Patients				Statistical test	
										p_1-p_2	p_{UL}-p_2
Study	***n***	**Age** [a]	**Formula for SL SL-values**	**% intended to exclude (number)**	**95%- CI**	**group**	***n***	**% abnormal, score outside SL (number)**	**95%-CI**	***p*-value**	
Coherence level											
Raymond & Sorensen (1998) [17]	10	9.9	*M* + 2.82 *SD* = 27.8%	0.2% (*n* = 0)	0-31	dyslexia	10	60% (*n* = 6)	26-88	< .01	*ns*
MacKay et al (2005) [24]	19	9.8	deficit ratio > 2	-	-	VLBW	19	47% (*n* = 9)	24-71	-	-
Pellicano & Gibson (2008) [27]	61	6.7	*z* > 1.65	5% (*n* = 3)	1-14	autism	20	40% (*n* = 8)	19-63	< .01	.01
						dyslexia	41	36% (*n* = 7)	15-59	.05	*ns*
Ho et al (2005) [28]	25	4.6	*M* + 1.64 *SD* = 71%	5% (*n* = 1 per 25)	0-20	amblyopia FE	21	14% (*n* = 3)	3-36	*ns*	*ns*
	25	7.5	*M* + 1.64 *SD* = 48%								
	25	10.6	*M* + 1.64 *SD* = 35%								
Wang et al (2007) [30]	32	7.3	*M* + 1.64 *SD* = 44%	5% (*n* = 2)	1-21	amblyopia FE	6	17% (*n* = 1)	0-64	*ns*	*ns*
Milne et al (2006) [26]	23	10.3	*z* >1.65	5% (*n* = 1)	0-22	autism spectrum disorder	23	22% (*n* = 5)	7-44	*ns*	*ns*
D_{max}											
Ho et al (2005) [28]	25	4.6	*M* ± 1.97 *SD* = 0.35 & 1.45 deg	2.5% [b] (*n* = 1 per 25)	0-20	amblyopia FE	21	D_{max_e} : 19% (*n* = 4)	5-42	.04	*ns*
	25	7.5	*M* ± 1.97 *SD* = 0.50 & 1.56 deg					D_{max_d} 10% (*n* = 2)	1-30	*ns*	*ns*
	25	10.6	*M* ± 1.97 *SD* = 0.57 & 1.43 deg								

SL = sample limit, FE = fellow eye/non-amblyopic eye, D_{max_e} = D_{max} is elevated, D_{max_d} = D_{max} is depressed, p_1-p_2 is the difference between observed proportions between patients and controls. The intended percentage excluded was used as observed proportion for controls, p_{UL}-p_2 is the difference between the observed proportion excluded patients and the upper limit of 95%-CI of the normal population. [a] mean age or age range in years; [b] 2.5% is excluded by using lower sample limit or upper sample limit. A total of 5% will be excluded if both SLs are used.

Table 4b. Estimated normal limits in motion-defined form studies, the intended percentages of persons in the general population that are excluded by use of the estimated limit and labelled as abnormal performers, precision of sample limits (95%-CI), and percentages of abnormal performing patients according to the sample limits.

	Controls					Patients				Statistical test	
										p_1-p_2	p_{UL}-p_2
Study	***n***	**Age** [a]	**Formula for SL SL-values**	**% intended to exclude (number)**	**95%- CI**	**group**	***n***	**% abnormal, score outside SL (number)**	**95%-CI**	***p*-value**	
Minimum dot speed											
Ho et al (2005) [28]	25	4.6	*M* + 1.64 *SD* = 0.50 deg/s	5% (*n* = 1 per 25)	0-20	amblyopia FE	21	24% (*n* = 5)	8-47	.01	*ns*
	25	7.5	*M*+ 1.64 *SD* = 0.26 deg/s								
	25	10.6	*M* + 1.64 *SD* = 0.23 deg/s								
Wang et al (2007) [30]	32	7.3	*M* + 1.64 *SD* = 0.26 deg/s	5% (*n* = 2)	1-21	amblyopia FE	6	67% (*n* = 4)	22-96	< .01	.05
Giaschi et al (1992) [31]	10	4-6	*M* + 2.5 *SD* = 0.24 deg/s	0.6% (*n* = 0)	0-31	amblyopia FE	20	90% (*n* = 18)	68-99	< .01	< .01
	10	7-9	*M* + 2.5 *SD* = 0.10 deg/s			amblyopia AE		95% (*n* = 19)	75-100	< .01	< .01
	10	10-12	*M* + 2.5 *SD* = 0.14 deg/s								
Percentage correct											
Jakobson et al (2006) [33]	19	6.1	*M* - 2 *SD*	2.3% (*n* = 0)	0-18	preterm	43	47% (*n* = 20)	31-62	< .01	.02
	19	6.1	*M* - 3 *SD*	0.1% (*n* = 0)	0-18			33% (*n* = 14)	19-49	< .01	*ns*

SL = sample limit, FE = fellow eye/non-amblyopic eye, AE = amblyopic eye, p_1-p_2 is the difference between observed proportions between patients and controls. The intended percentage excluded was used as observed proportion for controls, p_{UL}-p_2 is the difference between the observed proportion excluded in patients and the upper limit of 95%-CI of the normal population. [a] mean age or age range

without providing evidence for symmetrical or normal distributions of scores. As a result of the relatively small sample sizes per age group (mean n = 23), wide precision intervals were observed; the difference between the intended percentage to exclude and the upper limit of its 95%-CI varied from 9 to 31%. The only normal limit, not based on group measurements but on individual performances, was the deficit ratio.[24] The patient's performance was considered abnormal if the threshold was at least twice that of their matched controls.

Developmental trends

To study possible developmental trends, we compared studies using similar tasks, based on published results. On average, control groups consisted of 27 participants per author-defined age group (range 8-93, median 21). No studies were found for children aged 2-3 years, whereas data were very limited for the ages 3-7 years and above 10 years.

In Figure 1A, mean results of control groups in global motion direction studies and their estimated p_{90} are represented.[17, 25, 27, 28, 30] Mean scores and the estimated p_{90} seem to decrease significantly with increasing age, suggesting that the minimum proportion of coherent moving dots, needed to identify the motion direction correctly, becomes smaller with age. Mean coherence level and the estimated normal limit are negatively related to age (mean ρ = -0.61; $p < .03$; p_{90} ρ = -0.64; $p < .02$). This is illustrated by the linear trend lines in the figure, because the quadratic effect was not significant. Additionally, residual analysis of the trend line for p_{90} indicated the risk of overestimation of performances in multiple age groups, with a maximum of 14% coherence. The overestimation of performances could lead to an undesirably high number of performers labelled as abnormal. Because of the unreliability of the estimators and the risk of overestimation of performance, we consider the trend line not the best way to evaluate the performance of clinically evaluated children. One should use all information in the graph, position each clinically tested child against the data from the presented studies.

In Figure 1B, means and estimated p_{90}s are illustrated for two global motion target location studies with motion coherence thresholds. No sample limits were reported in these articles.[19, 20] Mean coherence level and the estimated p_{90} are negatively related to age (ρ = -0.71; p = .06). Again, the mean scores and the estimated p_{90} seem to decrease significantly with increasing age and visual inspection seems to indicate that there is a quadratic trend, although the regression estimators for age are not significant, probably due to the low number of data points. Therefore, the trend lines only illustrate the overall mean coherence level and the overall mean of the p_{90}'s.

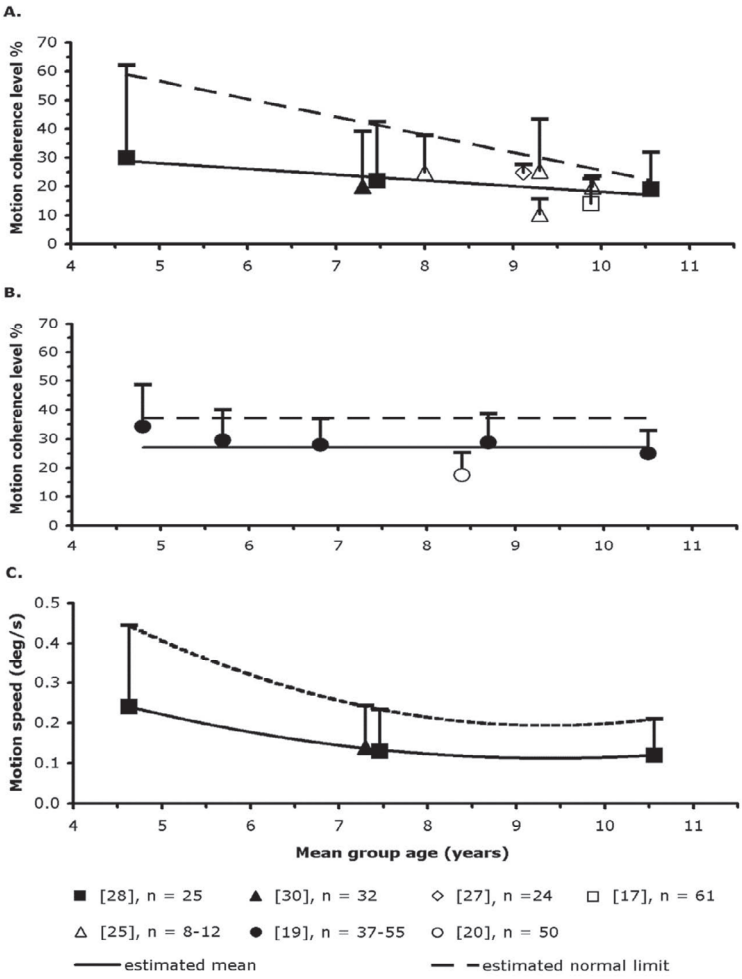

Figure 1. Mean results and mean + 1.28 *SD* for studies with comparable motion perception stimuli with a black background and white dots
1A. Global motion studies with a single target RDK and motion direction as response are represented. Symbols represent different studies: Ho et al,[28] Wang et al,[30] Pellicano & Gibson,[27] Raymond & Sorensen[17] and Chow & Ho.[25] Dot speed, test distance varied per study. Linear regression trend was significant.
1B. Global motion studies with two RDKs and with target location as response are represented: O'Brien et al[20] and Gunn et al.[19] Regression estimators, except constant, were not significant.
1C. Motion-defined form studies with naming as response are represented: Wang et al[30] and Ho et al.[28] Curvilinear trend was significant, but is considered not generalisable.

In Figure 1C, we present a comparison of two studies on motion-defined form.[28, 30] There seems to be a clear curvilinear negative trend: a perfect negative Spearman correlation was found (ρ = -1.00; p < .01) between these four data points and age. Younger children need a higher dot speed in order to name a motion-defined form correctly.

Patients' performance compared to typically developing children

Below, we summarize the results for each patient group, focussing on mean differences and differences in abnormal performers. On average, control groups consisted of 27 participants per author-defined age group (range 8-93, median 21) and the sample sizes of patient groups varied between 6 and 43. The percentage of abnormal performing patients and applied statistics for comparisons can be found in the last column of Table 4a-b. Tables with mean differences between patients and controls have been included in the Appendix 2 (Included studies – comparative studies).

- Children with *amblyopia*, tested in the non-amblyopic eye, performed significantly worse than age-matched controls on motion-defined form tasks ($p < .01$,[28] $p < .04$[30]), but not on global motion tasks.[28, 30] The percentage abnormal performers was significantly higher in one global motion task[28] and all three motion-defined form studies.[28, 30, 31]
- Children with *autism* perform worse, compared to age-matched controls, on a motion direction task using vertical motion ($p < .01$)[27] or rotational motion ($p < .01$),[15] but not on a horizontal motion task.[15] Compared to verbal mental age-matched controls, children with autism perform equally well or even outperform the controls on motion direction tasks (horizontal motion: $p < .05$).[15] Children with *autism spectrum disorder* did not perform significantly different from age-matched controls on global motion location tasks.[26] In one of two studies reporting the percentage abnormal performers, the percentage abnormally performing patients was significantly higher than in controls.[27] The percentage abnormal performers[27] was even significantly higher than the population limit of 14% (the upper limit of the controls' 95%-CI), indicating that children with autism have an increased risk to perform abnormally on global motion tasks.
- Children with *dyslexia*, compared to age-matched controls, perform worse on global motion direction tasks (all $p < .01$).[17, 25, 27] Their performance seems to deteriorate with increasing number of frames[17] and to improve if blue dots are used instead of red or white dots.[25] The percentage abnormally performing patients is significantly higher than that observed in the control group.[17, 27]
- Currently, there is no evidence that children with pure *dyspraxia* perform worse than age-matched controls on a global motion target location task.[20]
- To assess whether or not children with *hemiplegia* of heterogeneous aetiology performed worse than their controls on a global motion location

task, we performed a post-hoc t-test on the summary data. Children with hemiplegia performed significantly worse ($p < .01$).[19]

- There is no evidence, that children with *intellectual disability* perform worse than mental age-matched controls on a biological motion task.[13]
- *Prematurely born* children with complications, like retinopathy of prematurity and/or periventricular brain injury, seem to perform worse on motion-defined form tasks ($p < .05$), whereas those without complications do not perform significantly different from controls.[33] Although the observed percentage abnormal performers was significantly higher than observed in controls for both sample limits, the percentage abnormally performing patients was only significantly higher than expected in the general population for the sample limit 'mean minus 2 *SD*'.
- Children with *very low birth weight* (<1500 g), compared to age-matched controls, perform worse on a global motion direction task ($p < .01$).[24]
- Children with *Williams syndrome*, as compared to mental age-matched controls, perform significantly worse on a motion-defined form task, in which a target had to be located ($p < .01$)[14], and on a 3D global motion task ($p < .01$),[12] but not on 2D or simple global motion tasks.[12, 14] They perform equally well or even outperform mental age-matched controls on biological motion tasks ($p < .05$).[14, 16]

We conclude that, considering group mean performances, multiple patient groups perform significantly worse than controls on one or more motion perception tasks.

In a majority of studies reporting a sample limit, the percentage of abnormal performers, too, was significantly higher in patients than in controls. However, if the upper limit of the 95%-confidence interval of mean performance, as calculated by us (Table 4a and 4b), would be considered as the true population limit, there is only limited evidence for an increased risk of abnormal performance on global motion direction tasks in children with autism, and on motion-defined form tasks in children with monocular amblyopia and prematurely born children.

DISCUSSION

This systematic review shows that investigators around the world have invested considerable energy into the development and evaluation of tests, in order to enable quantified judgement of aspects of motion perception in

children. It appears that global motion has been studied most extensively, whereas a smaller number of studies focussed on motion-defined form and biological motion. Because this field is still in a pioneering phase, there is a wide variety of task characteristics, procedures and thresholds. Sample sizes of age-groups are still small, so currently available estimates of normal limits are insufficiently precise. First results suggest that developmental trends are present for global motion and motion-defined form, whereas insufficient data are available for biological motion. Based on comparison studies, first potential risk groups have been identified. However, we must conclude that at this stage, no motion perception tasks have been evaluated satisfactorily for application as diagnostic instruments in clinical practice.

In our opinion, building further upon these pioneering activities, further research should focus on international consensus development, test standardisation and collaboration of research groups, in order to include satisfactory study samples.

Consensus is needed on: 1. tasks characteristics and task procedures; 2. (estimated) normal limits and age groups; 3. confounding risks for task performances and group differences. We have formulated the following first suggestions:

Ad 1. Because stimuli with a black background and white dots are most common, we suggest that at least a black and white stimulus should be included in all studies.

Dot life-time should be limited, to prevent single dot tracking and dot speed and motion direction should also be standardised.

The choice of dot speed might depend on the brain systems one wants to study, and on the presence of additional disorders, like nystagmus. The indication that the activity of V1 decreases with increasing motion speed and that a direct route from the retina to the superior colliculus and pulvinar to the prestriate cortex might also be involved in motion perception,[39, 40] could be a good reason to study multiple speeds. In this way, the integrity or developmental status of multiple routes could be studied. We suggest, that at least a slow speed (< 6 deg/s), at which V1 is activated before V5, and a high speed task (> 15 deg/s), at which the colliculo-prestriate cortical route is assumed to be the primary route, are studied.

The co-presence of nystagmus warrants special attention. In patients with congenital nystagmus, adaptive perceptual processes that are considered to prevent oscilliscopia (illusory motion of the visual world) are suggested to result in a loss of sensitivity to motion of a stimulus.[38, 41, 42] Elevated thresholds as a result of adaptive perceptual processes seem to be more likely at low

speeds,[38, 42] horizontal motion direction, which is often the direction of the major component in congenital nystagmus,[38, 41] and larger stimulus size.[38] If the retinal image motion in patients with congenital nystagmus is simulated, by adding continuous sinusoidal or ramp motion to stimuli for controls, motion sensitivity of patients with nystagmus seems similar to that of controls.[41] If congenital nystagmus is present in the patient group, as additional disorder, one might consider studying vertical motion with a high dot speed, or an analysis including and excluding patients with nystagmus, for an indication of the effect of nystagmus on the results.

Considering the stimuli described in this review and the above mentioned criteria, we conclude for pragmatic reasons that the stimuli described by the following authors may be eligible for standardisation of slow speed stimuli: Pellicano and Gibson[27] for global motion direction if dot speed is slightly reduced, Milne and co-authors [26] or O'brien and co-authors,[20] for global motion target location if limited dot life-time is guaranteed, and Reiss and co-authors[14] for biological motion.

Target location stimuli for global motion and biological motion are preferable in young children, because target detection tasks appear to be easier to accomplish than motion direction tasks at that age.

Although no limited dot life-time seems to be used in motion-defined form stimuli, the stimuli described by Ho et al[28] are studied most extensively and therefore may be eligible for standardisation.

At this moment, we have no suggestions for high-speed stimuli with a black background and white dots, because this has infrequently been studied and only was used in motion direction tasks.

Ad 2. Current sample sizes are too small to set reliable sample limits and to estimate the prevalence of motion perception problems. Reliable percentile norms would require groups of at least 120 participants per age category.[43] Which age groups should be studied, could be determined by studying the developmental trend more extensively, ideally by doing a longitudinal study. However, this would take many years and participants' performances might improve over time, due to growing task experience. The alternative is to cross-sectionally study large study populations and identify relevant age groups in the analysis. We realise that large samples, specifically of patients, are difficult to recruit and therefore might require international collaboration of research groups.

Other normal limits than sample-based limits, such as a deficit ratio, seem to be unsuitable for diagnostic purposes, because if a patient is matched to a single control, normal variation in controls is disregarded and there is a risk of erroneous judgements.

Ad 3. Another matter that needs consideration concerns factors that may confound task performances. We presume that age, visual acuity and IQ or socio-economic status (SES) are possible confounders or indicators for confounders. Age needs no discussion, because of the developmental trends observed in many studies. Visual acuity, SES and IQ might be less obvious. Most studies used a dot size larger than 3 arcmin, indicating that a single dot should be visible for children with low vision (visual acuity < 0.3). However, the presence of multiple dots might influence visibility, perception and task performance negatively. The assumption of normal visual acuity and therefore visibility of the stimulus is realistic in controls, but not in patients. Subnormal visual acuity or even low vision can be missed easily, especially in children with motor or intellectual disabilities. Either it should be checked that a stimulus and its details at near distance are equally visible for patients and controls, or the effect of visual acuity should be specifically addressed in the analysis. Information on SES and/or IQ should be included, too. Although we could not find articles on SES or IQ in relation to motion perception, there is some evidence that SES and environmental factors related to SES may influence IQ[44, 45] as well as neural system development and cognitive functioning.[8, 46] Small group differences were found between low SES en moderate SES on tasks for visual cognition (ventral stream) and spatial cognition (dorsal stream).[8, 46] Information on IQ or SES in the control group could also be used to rule out selection bias for the control group.

At this stage, what can we do in clinical practice? We cannot yet reliably label individual children as normal or abnormal performers. By calculating 95%-confidence intervals for sample limits of typically developing children, we were able to indicate maximum percentages of the typical population that are likely to score above the sample p90-score. Accepting the fact that the maximum percentage could be true, one is able to say that a score above this limit indicates that a participant belongs to the weakest performers, as an indication of risk. So, we may already introduce motion perception tasks as observational instruments with quantifiable outcomes, and deliver very cautious statements about children's performances.

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Appendix 1

Table 1. Characteristics of the global motion studies

Table 2. Characteristics of motion-defined form studies

Table 3. Characteristics of the biological motion studies

Table 1. Characteristics of the global motion studies: thresholds, responses, stimulus characteristics (stimulus type, motion direction, speed, dot size) and test distance.

Threshold	Response	Stimulus type	Motion direction per trial	Speed (deg/s)	Dot size (arcmin)	Test distance (cm)
1. Motion coherence level [1-17] 2. D_{max} [4, 6]	1. Motion direction [1, 3-6, 11-14, 16] 2. Target location [2, 7-10, 15] 3. Target or non-target [17]	1. RDK, black background white dots [1-10, 13, 15, 17] - Single RDK o Target RDK [1, 3-6, 13] o Target RDK or noise-RDK [17] o 3D target RDK or (2D) noise RDK [17] - RDK adjacent to noise-RDK [1] - RDKs left and right of the centre o Target RDK vs noise-RDK [2, 15] o RDK with target strip vs undivided-RDK [7-10] 2. Single RDK, black background colour dots [13] 3. Single RDK, white background black dots [12, 14] 4. Single RDK, grey background black and white dots [16] 5. Single RGK (circular random gabor kinematogram) with static noise background [11] - Gabors luminance modulated - Gabors contrast modulated	1. up or down [3-6, 11, 12, 14] 2. left or right [1, 2, 13, 16] 3. oscillating horizontal motion [7-10, 15] 4. 0-360 deg (pseudo-random) [17] 5. rotation on spherical surface [17] 6. rotation clockwise or anti-clockwise [16] 7. contraction or expansion [16]	Slow (< 6 deg/s) - 1.2 [6] - 1.26 [4, 5] - 1.5 [11] - 2.0 [17] - 2.5 [2] - 3.0 [17] - 5.3 [10] - 5.8 [7, 8] Intermediate (6-15 deg/s) - 6 [9, 11] - 6.3 [3] - 7.0 [15] - 9.0 [11] - 10 [16] - 11 [1] High (> 15 deg/s) - 18 [12, 14]	- 0.84 [4, 5] - 2.5 [1] - 3 [13] - 6 [15] - 6.6 [3] - 6.7x10.1 [17] - 22.8 [2] - 24 [16] - 30 [12, 14]	- 40 [9, 10] - 50 [1, 3, 7, 8, 14] - 56 [17] - 57 [11, 15, 16] - 61 [2] - 65 [13] - 140 [4-6]

Table 2. Characteristics of motion-defined form studies: thresholds, responses, stimulus characteristics (stimulus type, motion direction, speed, dot size) and test distance.

Threshold	Response	Stimulus type	Motion direction per trial	Speed (deg/s)	Dot size (arcmin)	Test distance (cm)
1. Minimum dots speed [4-6, 18] 2. Accuracy - Weighted percentage correct response [19] - percentage correct response [20] 3. Motion coherence level [2]	1. Identification - Form [4-6] - Letter [18] 2. Gap position [19, 20] 3. Target location [2]	1. RDK, black background, white dots - With 1 of 5 forms (circle, duck, fish, heart, gingerbread man) [4-6] - With 1 of 10 letters [18] - With Landolt C in 1 of 4 orientations, [19] - With E in 1 of 4 orientations [20] - RDK left and right of centre, target RDK contains vertical rectangular figure, non-target RDK contains horizontal rectangular figure [2]	1. motion in form opposite to background motion - left or right [2, 18, 20] - up or down [4-6] 2. left or right in form and static background [19]	Slow (< 6 deg/s) - 0.021 - 0.68, [20] - 0.039 - 1.26 [4-6] - ≤0.45 [18] - 1.3 [19] - 2.51 [2]	- 3.8 [4-6] - 15.6 [18] - 22.8 [2]	- 61 [2] - 100 [19] - 200 [20] - 560 [4, 5] - 580 [6] - 600 [18]

Table 3. Characteristics of the biological motion studies: thresholds, responses, stimulus characteristics (stimulus type, motion direction, speed, dot size) and test distance.

Threshold	Response	Stimulus type	Motion direction per trial	Speed (deg/s)	Dot size (arcmin)	Test distance (cm)
1. Accuracy [21-25] - number of correct responses [23-25] - percentage correct response [22] - d' , unbiased measure of sensitivity [21] 2. Minimum exposure duration [26] 3. Reaction time [23] 4. Noise at certain accuracy level - Number of noise dots [25] - Motion coherence level [2]	1. Naming - Naming only [26] - Naming and report facing direction of figure and motion direction [24] 2. Target or non-target [21, 23, 25] 3. Walking direction [22] 4. Target location [2]	1. Point-light figure, black background, white dots [2, 22-24, 26] - Single figure, walking human or object (bicycle, ball, scissors, chair) [26] - Single figure, 1 of 4 figures (walking man, running dog, walking dog, bird) [24] - Target, 1 of 3 human activities (walking, jumping, waving), or non-target, phase scrambled point-light figure [23] o without noise o with pseudo-random noise - target, walking man, in noise [22] o static noise o random moving noise o yoked moving noise - Target, walking man, vs non-target, phase scrambled point-light figure, left and right of the centre o With yoked moving noise [2] 2. Point-light figure, grey background, black dots [21, 25] - Target, 1 of 5 human activities (running, kicking, climbing, throwing, jumping) or, phase scrambled point-light figure o Without noise o With noise	object motion direction - across screen o left or right [26] - like in treadmill o left or right [2, 21-25] o frontal (bird) [24]	Slow (< 6 deg/s) - 2.51 [2] - 4 [21, 25] gait cycle 1.76 sec [24] 2.0 sec [2] fly cycle [24] 1.98 sec	- 10 [25] - 12 [21] - 13.8 [24] - 15 [22] - 22.8 [2]	- 41 [21] - 60 [25] - 61 [2] - 92 [22] - 200 [24]

1 arcmin = 1/60 degree. For a visual acuity of 1.0 one has to be able to discriminate an element 1 arcmin in size, a Snellen-E of 5 arcmin.
d' , unbiased measure of sensitivity, is based on hits (target indicated as target) and false alarms (non-target indicated as target). A higher positive value indicates a higher sensitivity to the target.

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Appendix 2

Included studies - Comparative data

1. Amblyopia
2. Autism
3. Dyslexia
4. Dyspraxia
5. Hemiplegia
6. Intellectual disability
7. Premature born children
8. Children with very low birth weight
9. Williams syndrome

Included studies - Developmental data

Excluded studies - Comparative data

Excluded studies - Developmental data

Included studies – comparative studies

1. Amblyopia

Global motion & Motion-defined form
Global motion studies with motion direction as response and motion coherence level (%;(Signal dots/(Signal dots + Noise dots)*100) and/or D_{max} (deg) as outcome. Motion-defined form studies with identification as response and minimum dots speed (deg/s) as outcome.

Ho et al (2005)[1]

	Amblyopia, non-amblyopic eye	Controls	Statistics
n	21	21	
Gender (% male)	-	-	
Age range in years (mean; *SD*)	4.4-11.0 (6.9; 1.7)	4.3-11.2 (7.0; 1.9)	
IQ information	-	-	
Motion perception			MANOVA Group: $F(3, 38) = 4.71$, $p < .01$
Global motion			
Mean motion coherence % [a] (*SD*; range)	26 [b] (22; 3-81)	25 (18)	$F(1, 40) = 0.01$, $p = .91$, $f = 0.00$
D_{max} deg [a] (*SD*; range)	1.24 [b] (0.79; 0.49-3.70)	1.04 (0.26)	$F(1, 40) = 0.23$, $p = .63$; $f = 0.08$
Motion-defined form			
Minimum dots speed deg/s [a] (*SD*; range)	0.20 [b] (0.13; 0.07-0.61)	0.10 (0,04)	$F(1, 40) = 13.55$, $p < .01$; $f = 0.58$

[a] Data was extracted from table with individual data and figure with group results; [b] Results if abnormal performers are excluded: Motion coherence %: 19 (14; 3-47); D_{max} : 0.99 (0.24; 0.55-1.37); deg/s: 0.16 (0.08; 0.07-0.34).

Wang et al (2007)[2]

	Amblyopia, non-amblyopic eye	Controls	Statistics [a]
n	6	32	
Gender (% male)		-	
Age range in years (mean; *SD*)	5.81-8.66 (6.8; 1.1)	5-8 (7.3; 1.1)	
IQ information	-	-	
Motion perception			MANOVA Group: $F(2, 9) = 4.50$, $p < .04$
Global motion			
Mean motion coherence % (*SD*; range)	20 (16; 9-47)	20 (15)	$F(1, 10) = 4.133$, $p < .07$, *ns*
Motion defined form			
Mean minimum dot speed deg/sec (*SD*; range)	0.39 (0.32; 0.07-0.91)	0.14 (0.08)	*ns*

[a] an age matched control group ($n = 6$) was used for analysis (mean age 6.8 years, $SD = 1.1$), post-hoc univariate F-test was controlled for multiple comparisons with Bonferroni adjustment set at 0.025 for each task. Also a texture defined task was used.

2. Autism

Global motion
Global motion study with target location as response and motion coherence level (%;(Signal dots/(Signal dots + Noise dots)*100) as outcome.

Milne et al (2006)[3]

	Autism spectrum disorder	Controls	Statistics
n	23	23	
Gender (% male)	96	43	
Age range in years (mean; *SD*)	8.0-12.92 (10.08; 1.67)	8.83-12.33 (10.25; 1.08)	
Mean non-verbal IQ [a] (*SD*; range)	95 (14.2; 70-122)	102 (14.1; 84-130)	
Global motion			
Mean motion coherence level % (*SD*; range)	17.09 (15.22; 6.24-55.14)	10.26 (4.13; 3.55-19.65)	Mann-Witney: *ns*

[a] Outcomes of Raven's (standard) progressive matrices were used to calculate non-verbal IQ.

Global motion
Global motion studies with motion direction as response and motion sensitivity ((Signal dots +Noise dots)/Signal dots) or motion coherence level (%;(Signal dots/Noise dots)*100) as outcome.

Del Viva et al (2006)[4]

	Autism	Age matched controls	Verbal mental age matched controls	Statistics
n	10	14	12	
Gender (% male)	-	-	-	
Age range in years (mean; *SD*)	6.0-14.1 (8.8; 3.0)	8.0-11.9 (9.7;0.8)	6.1-7.2 (6.6; 0.3)	
Mean verbal mental age years [a]	6.7 (2.5;4.4-12.3)	-	matched	
Global motion				
Mean motion sensitivity (%) per test condition				ANOVA Group: $F = 5.8$, $p < .01$ Control groups: $p < .05$ Patients vs. age-matched controls: *ns* Patients vs. verbal mental age matched controls: *ns*
Rotation (*SD*; range)	14.4 (3.7; 7.9-21.2)	23.1 (5.2;12.7-30.4)	18.2 (6.0; 9.0-27.2)	Student t-test Patients vs. Age-matched controls: Rotation: $p < .01$ Expansion & horizontal: *ns* Patients vs. Verbal mental age matched controls: Horizontal: $p = .02$ Expansion ($p = .1$) & rotation ($p = .05$): *ns*
Horizontal (*SD*; range)	20.3 (7.8;12.0-36.8)	18.1 (2.7;13.1-21.9)	14.4 (2.8; 11.7-19.2)	
Contraction/ Expansion (*SD*; range)	15.1 (3.0; 11.1-22.3)	16.1 (3.8;11.7-26)	13.3 (2.1; 9.1-16.5)	

[a] Data of the WISC-R was used to estimate the verbal mental age ((chronological age*VIQ)/100). The reported mean verbal age is that of the total patient group ($n = 13$, mean chronological age in years = 10.9, $SD = 4.2$).

Pellicano & Gibson (2008)[5]

	Autism	Controls	Statistics [ab]
n	20	61	
Gender (% male)	90	77	
Age range in years (mean; *SD*)	8.08-12.33 (9.59; 1.38)	8.00-12.58 (9.88; 1.01)	
Mean non-verbal IQ [c] (*SD*)	107.10 (8.95)	106.82 (12.90)	
Verbal IQ [c] (*SD*)	97.00 (15.25)	104.28 (11.60)	
Global motion			
Mean motion coherence level % (*SD*; range)	22.40 (13.78; 5.31-54.44)	14.02 (6.70; 4.41-40.53)	ANOVA Group: $F(2, 119) = 10.82$, $p < .001$ $t(119) = 2.41$, $p < .01$, $d = 1.01$

[a] Effect of outliers was reduced by scores more than 3 *SD* above/below the group mean were replaced by a score at 2.5 *SD* before calculation of standard scores and analysis took place; [b] Also a group with dyslexia was included. Autism vs. dyslexia: $t(119) = 1.08$, *ns*; [c] Outcomes of Raven's (standard) progressive matrices or Wechsler Abbreviated Scale of Intelligence (WASI) were used to assess non-verbal IQ, outcomes of the Peabody Picture Vocabulary Test or Wechsler Abbreviated Scale of Intelligence were used to assess verbal IQ.

3. Dyslexia

Global motion
Global motion studies with motion direction as response and motion coherence level (%;(Signal dots/(Signal dots + Noise dots)*100) as outcome.

Raymond & Sorensen (1998)[6]

Experiment 1a [a]	**Dyslexia**	**Controls**		**Statistics**
n	10	10		
Gender (% male)	50	50		
Age range in years (Mean; *SD*)	7.3-11.3 (9.9; 1.2)	7.3-11.3 (9.9; 1.2)		
Mean IQ (*SD*)	98 (9.8)	At least average		
Reading level	At least 1.5 years below age level	Assumed at age level		
Global motion				
Mean motion coherence level (%) per stimulus condition				
Noise and no-noise, 60 ms (*SD*; range [b])	39.8 (17.2; 18-70)	19.9 (2.9; 17-26)		$p < .01$
Experiment 2	**Dyslexia**	**Controls**	**Controls**	**Statistics**
n	12	12	8	
Gender (% male)	50	41	38	
Age range in years (mean; *SD*)	- (11.6)	- (9.3)	- (8.0)	
IQ Mean (*SD*)	-	-		
Reading level	At least 1.5 years below age level	Assumed at age level		
Global motion				
Mean motion coherence level (%) per stimulus condition				
2 short frames, 64 ms (*SD*; range) [b]	26.3 (15; 14-56)	25.4 (14; 9-48)	-	*ns*
7 short-frames, 224 ms (*SD*; range) [b]	19.9 (8; 8-34)	10.5 (4; 4-16)	-	$p < .01$
2 long-frames, 224 ms (*SD*; range) [b]	-	-	25 (10; 11-41)	

[a] Experiment 1b is excluded, because the sample size of the control group was too small; [b] Data was partially extracted from a figure with individual results.

Chow & Ho (2005)[7]

	Dyslexia	Controls	Statistics
n	24	24	
Gender (% male)	-	-	
Age range in years (mean; *SD*)	- (9.16; 1.38)	- (9.12; 1.29)	
Mean non-verbal IQ [a] (*SD*)	106.21 (8.28)	106.00 (7.10)	
Global motion			
Mean motion coherence level (%) per test condition			
White dots (*SD*)	36.59 (8.63)	24.73 (2.26)	Two-way mixed design ANOVA: Group x Colour: $F(2,41) = 5.83$, $p < .01$ Group: $F(1,47) = 37.58$, $p < .01$
Blue dots (*SD*)	31.97 (7.91)	23.30 (0.87)	
Red dots (*SD*)	35.83 (10.62)	24.81 (1.93)	
Total (*SD*)	34.80 (9.23)	24.28 (1.90)	

[a] Outcomes of Raven's (standard) progressive matrices were used to calculate non-verbal IQ.

Pellicano & Gibson (2008)[5]

	Dyslexia	Controls	Statistics [ab]
n	41	61	
Gender (% male)	63	77	
Age range in years (mean; *SD*)	8.08-12.33 (9.97; 1.10)	8.00-12.58 (9.88; 1.01)	
Mean non-verbal IQ [c]	106.76 (11.38)	106.82 (12.90)	
Verbal IQ [c] (*SD*)	110.15 (10.05)	104.28 (11.60)	
Global motion			
Mean motion coherence level % (*SD*; range)	26.38 (19.60; 5.19-75.50)	14.02 (6.70; 4.41-40.53)	ANOVA Group: $F(2, 119) = 10.82$, $p < .001$ $t(119) = 4.54$, $p < .001$, $d = 1.32$

[a] Effect of outliers was reduced by scores more than 3 *SD* above/below the group mean were replaced by a score at 2.5 *SD* before calculation of standard scores and analysis took place; [b] Also a group with dyslexia was included. Autism vs. dyslexia: $t(119) = 1.08$, *ns*; [c] Outcomes of Raven's (standard) progressive matrices or Wechsler Abbreviated Scale of Intelligence (WASI) were used to assess non-verbal IQ, outcomes of the Peabody Picture Vocabulary Test or Wechsler Abbreviated Scale of Intelligence were used to assess verbal IQ.

4. Dyspraxia

Global motion
Global motion study with target location as response and motion coherence level (%;(Signal dots/Noise dots)*100) as outcome.

O'Brien et al (2002)[8]

	Pure dyspraxia	Chronological age and verbal mental age matched controls	Statistics
n	8	50	$F(1,56) = 1.2$; *ns*
Gender (% male)	75	-	
Age range in years (mean; *SD*)	7-11 (8.2; 1.5)	matched (8.4)	
Verbal mental age [a]	matched	matched	
Global motion			
Mean motion coherence level % (*SD*)	14.9 (7.9)	17.5 (6.1)	

[a] Outcomes of the British Picture Vocabulary Scale were used to estimate mental age.

5. Hemiplegia

Global motion

Global motion study with target location as response and motion coherence level as outcome.

Gunn et al (2002)[9] Threshold: Motion coherence level (%); Response: target Location

	Hemiplegia [a]	Controls	Statistics
n	22	295	repeated measure ANOVA with age as covariate: interaction task*group [b]: $F(1,381) = 5.6$; $p < .02$ t-test done by reviewers for threshold difference $p < .01$
Gender (% male)			
Age range in years (mean; *SD*)	3.2-12.4 (-)	4.10 –11.99 (-)	
IQ information	-	-	
Global motion			
Mean coherence level % (*SD*; range)	36.8 (10.4; 26.4-61.4)	28.8 (8.4)	

[a] Two patients were excluded because of the age criterion, data was therefore estimated from figures with individual data; [b] also a global form task was done.

6. Intellectual disability

Biological motion
Biological motion study with identification as response and minimum exposure duration as outcome.

Moore et al (1995)[10] Threshold:Minimum exposure duration (ms), response naming

	Intellectually disabled	Verbal mental age matched controls	Statistics
n	15	15	
Gender (% male)	-	-	
Age range in years (mean; *SD*)	9.75 -16.42 (14.17; 1.67)	11.92-10.58 (8.42;1.17)	
Verbal mental age [a] (mean, *SD*)	6.00-10.33 (8.08; 1.33)	6.25-10.33 (8.33; 1.25)	
Verbal IQ [a] (mean, *SD*)	61.5 (7.3; 49-71)	100.4 (4.3; 91-106)	
Biological motion			
Mean exposure duration in ms per test condition [b]			
First presentation: 5PLW [c] (*SD*; range)	203 -	309 -	Sign test: *ns*
Second presentation: 10PLW [c] (*SD*; range)	123 -	149 -	Sign test: *ns*
Total (*SD*; range)	163 -	229 -	Sign test: $p = .09$, *ns*

[a] Outcomes of the British Picture Vocabulary Scale were used to match subjects pair wise and assess verbal IQ; [b] Data was partially extracted from a figure with individual results; [c] 5PLW = point-light walker made of 5 dots, 10PLW is point-light walker made of 10 dots.

7. Premature born children

Motion-defined form

Motion-defined form study with gap position location as response and percentage correct responses as outcome.

Jakobson et al (2006)[11] Threshold: Percentage correct response &, response: gap position

	Preterm					Age and SES matched full-term controls	Statistics
	No ROP and PVBI	ROP only	PVBI only	ROP and PVBI	Total		
n	11	12	10	10	43	19	
Gender (% male)	-	-	-	-	34	47	
Age range in years (mean; *SD*)	-	-	-	-	5.25-6.83 (6.08; 0.52)	5.25-6.83 (6.08; 0.52)	
IQ information	-	-	-	-			
Performance IQ (*SD*)	-	-	-	-	90.5 (10.6)	109.3 (13.0)	
Verbal IQ (*SD*)	-	-	-	-	91.0 (10.8)	114.3 (16.0)	
Motion-defined letter							
correct % [a] (*SD*)	61 (14)	47 (11)	46 (13)	37 (13)	48 (16)	71 (19)	ANOVA Group: $F(4, 57) = 10.16$, $p < .01$, $\eta^2 = .42$ ROP vs. control PVBI vs. control ROP and PVBI vs. control: $p < .05$

PVBI = periventricular brain injury; ROP = retinopathy of prematurity; [a] Data partially extracted from a figure with group results.

8. Children with very low birth weight (VLBW)

Global motion
Global motion study with motion direction as response and motion coherence level (%;(Signal dots/(Signal dots + Noise dots)*100) as outcome.

MacKay et al (2005)[12]

	VLBW, without major neurological abnormalities	A term controls	Statistics [a]
n	19	19	
Gender (% male)	47	53	
Age range in years (mean; *SD*)	5.17-8.42 (6.83; 0.98)	4.92-8.92 (6.83; 1.28)	
Mean Verbal IQ (*SD*)	103.8 (9.8)	110.9 (6.9)	
Global motion			
Mean coherence level % (*SD*)	29.81 (29.20)	9.80 (11.72)	MANCOVA, controlling for age $F(5,29) = 4.12$, $p < .01$ Group: $p < .01$ $t(22) = -2.70$, $p < .05$

[a] Number of participants for analysis is 18, 1 control and 1 patient were not tested on global motion;[b] Peabody Picture Vocabulary Test- Third Edition was used to assess Verbal IQ.

9. Williams syndrome

Global motion, motion-defined form and biological motion
Global motion, motion-defined form and biological motion study with target location as response and motion coherence level (%;(Signal dots/(Signal dots + Noise dots)*100) as outcome.

Reiss et al (2005)[13]

	Williams Syndrome	Mental age matched controls	Statistics [c]
n	10	10	
Gender (% male)	-	-	
Age range in years (mean; *SD*)	9.25-18.3 (14.25; -)	4.92-7.58 (6.08; -)	
IQ test information [a]			
Composite IQ-score (*SD*)	63.7 (15.97)	119.50 (9.04)	
Mean verbal score (*SD*)	38.30 (7.72)	34.40 (5.22)	
Mean matrices score (*SD*)	20.80 (4.21)	20.10 (3.35)	
Mean coherence level (%) per test condition [b]			Mixed-model repeated measure ANOVA Group: $F(3, 36) = 3.10$, $p < .04$
Global motion (*SD*; range)	8 (5)	8 (-)	$t(18) < 1.54$, *ns*
Motion defined form (*SD*; range)	56 (11)	32 (7)	$t(18) = 4.01$, $p < .001$
Biological motion (*SD*; range)	23 (16)	36 (13)	$t(18) = 2.38$, $p < .04$

[a] Outcomes of the Kaufman Brief Intelligence Test were used to match patients to controls on mental age; [b] Data was extracted from a figure with group results; [c] Study also included adult groups

Biological motion
Biological motion study with walking direction as response and percentage correct responses as outcome.

Jordan et al (2002)[14] Percentage correct & walking direction

	Williams Syndrome	**Mental age matched controls**	**Statistics [b]**
n	10	10	
Gender (% male)	-	-	
Age range in years (mean; *SD*)	9.33-15.58 (11.58;-)	4.25-7.25 (6.0;-)	
IQ test information [a]			
Composite IQ-score (*SD*)	62.60 (15.72)	116.40 (9.83)	
Mean verbal score (*SD*)	33.15 (6.10)	31.60 (4.59)	
Mean matrices score (*SD*)	18.50 (2.56)	19.16 (3.35)	
Biological motion			
Mean percentage correct per test condition			Mixed-model repeated measures ANOVA Group x S/N ratio x Noise Type
S/N [c] ratio 1:1 (*SD*; range)	97.54 -	89.20 -	Groups: $F(2, 25) = 9.11$, $p < .01$ Post hoc comparison: $p < .01$
S/N [c] ratio 1:3 (*SD*; range)	84.26 -	77.78 -	Groups: $F(2, 25) = 9.45$, $p < .01$ Post hoc comparison: $p = .18$, *ns*
total (*SD*; range)	90.90 -	83.49 -	Groups: $F(2, 25) = 11.33$, $p < .01$ Post hoc comparison: $p < .05$

[a] Outcomes of the Kaufman Brief Intelligence Test was used to match patients to controls on mental age; [b] Study also included a group with adult controls, only group effect and post hoc comparison for the patients vs. mental-age matched controls are reported; [c] S/N = number of signal dots (S)/ number of noise dots (N)

Global motion
Global motion study with target or non-target as response and motion coherence level as outcome.

Mendes et al (2005)[15]

	Williams Syndrome	Mental age matched	Statistics [c]
n	6	11	
Gender (% male)	33	64	
Age range in years (mean; *SD*)	11-20 (16.00;3.52)	5-14 (9.09;3.08)	
Mental age	6.5-10 (8.67;1.44)		
IQ information [a]			
Performance IQ (*SD*)	44.3 (2.58)	-	
Verbal IQ (*SD*)	52 (6.98)	-	
Global motion			
Mean coherence level (%) per test condition [b]			Mann-Whitney
Global motion or noise (*SD*)	36 (12)	28 (7)	*ns*
3D global motion or 2D noise no time pressure (*SD*)	35 (12)	12 (2)	$p < .01$
3D global motion or 2D noise 200 ms per trial (*SD*)	31 (16)	26 (9)	$p = .02$

[a] WISC-3 or WAIS was used to assess IQ; [b] Data was extracted from a figure with group results; [c] Control group consisted of 8, 9, 8 age matched controls for consecutive test conditions. The patient group consisted of 5 patients in the 3D time constraint condition.

Included studies - Developmental data
Ordered by publication year

Global motion
Global motion study with letter identification as response and Minimum dots speed (deg/s) as outcome.

Giaschi et al (1992)[16]

	Controls			Total
	4-6 year olds	**7-9 year olds**	**10-12 year olds**	
n	10	10	10	30
Gender (% male)	-	-	-	-
Age range in years (mean; *SD*)	-	-	-	3.67 -13.5 (8.42-2.75)
IQ information	-	-	-	-
Motion-defined letter				
Mean minimum dot speed deg/s (*SD*; range)	0.14 (0.04)	0.05 (0.02)	0.06 (0.03)	-

Global motion
Global motion study with target location as response and motion coherence level as outcome.

Gunn et al (2002)[9]

	Controls [a]					Statistics
	4 year olds	**5 year olds**	**6-7 year olds**	**8-9 year olds**	**10-11 year olds**	
n	37	93	60	50	55	
Gender (% male)	-	-	-	-	-	
Age range in years (mean; *SD*)	4.10-5.29 (-)	5.30-5.99 (-)	6.00-7.99 (-)	8.00-9.99 (-)	10.00-11.99 (-)	
IQ information	-	-	-	-	-	
Global motion						
Mean motion coherence level % (*SD*; range)	34.2 (11.3)	29.5 (8.2)	28.0 (7.0)	28.8 (7.7)	24.9 (6.2)	$F(5,354) = 15.6$; $p < .001$

[a] data of adults is excluded

Global motion & Motion-defined form
Global motion study with motion direction as response and motion coherence level (%;(Signal dots/(Signal dots + Noise dots)*100) and/or D_{max} (deg) as outcome. Motion-defined form study with identification as response and minimum dots speed (deg/s) as outcome.

Ho et al (2005)[1]

	Controls		
	3-5 year olds	**6-8 year olds**	**9-11 year olds**
n	25	25	25
Gender (% male)	-	-	-
Age range in years (mean; *SD*)	- (4.63; 0.65)	- (7.46;0.88)	- (10.65; 0.93)
IQ information	-	-	-
Motion tests			
Global motion			
Mean motion coherence level % (*SD*; range)	30 (25)	22 (16)	19 (10)
Mean D_{max} deg (*SD*; range)	0.90 (0.28)	1.03 (0.27)	1.00 (0.22)
Motion-defined form			
Mean Minimum dots speed deg/s (*SD*; range)	0.24 (0.16)	0.13 (0.08)	0.12 (0.07)

Excluded studies - Comparative data
Ordered by publication year

Global motion
Global motion study with motion direction as response and coherence level as outcome.

Ellemberg et al (2002)[17]_1

	Congenital bilateral (CB) cataract [a]		Congenital unilateral (CU) cataract [a]			
	Best eye	**Worst eye**	**Non-deprived eye**	**Deprived eye**	**Controls**	**Statistics**
n	6	6	9	9	12	
Gender (% male)						
Age range in years (mean; *SD*)	5.0-11.7 (7.15; 2.42)	5.0-11.7 (7.15; 2.42)	4.1-12.1 (6.68; 2.24)	4.1-12.1 (6.68; 2.24)	- (6.0; 0.17)	
IQ information	-	-	-	-	-	
Global motion						ANOVA Group: $F(4, 54) = 4.40$, $p < .01$
Mean motion coherence level %	42.7 (16.5; 19-63)	45.5 (19.6; 26-75)	16.8 (4.2; 7-22)	15.6 (3.9; 7-19)	9.0[b]	CB and CU both eyes worse than controls: $p < .01$. [c]

Ellemberg et al (2002)[17]_2

	Developmental unilateral (DU) cataract [a]			
	Non-deprived eye	**Deprived eye**	**Controls**	**Statistics**
n	7	7	12	
Gender (% male)				
Age range in years (mean; *SD*)	6.0-12.5 (9.63; 2.09)	6.0-12.5 (9.63; 2.09)	- (6.0; 0.17)	
IQ information	-	-	-	
Global motion				
Mean motion coherence level %	10.1 (2.0; 8-14)	11.1 (1.6; 9-14)	9.0 (-) j	*ns*

[a] 2 patients with bilateral congenital cataract, 5 patients with unilateral congenital cataract and 2 patients with developmental cataract were excluded because they were older than 12.99 years of age. Bilateral developmental cataract was excluded because of the low number of remaining patients within the age criterion; [b] Data extracted from a figure with group results; [c] Patients with congenital unilateral cataract performed better with the deprived eye than patients with congenital bilateral cataract with either eye ($p < .01$). The performance with the deprived and the non-deprived eye of the patients with congenital unilateral cataract did not differ significantly.

Global motion
Global motion studies with target location as response and motion coherence level (%;(Signal dots/Noise dots)*100) as outcome.

Spencer et al (2000)[18]

	Autism	Controls	Statistics
n	23	50	
Gender (% male)	-	-	
Age range in years (mean; *SD*)	-	-	
Verbal mental age in years [a]	7-11	7-11	
Global motion			
Mean motion coherence level % (*SD*)	25.5	17.5	$F(1,72) = 10.98$, $p < .01$

[a] Test used to assess verbal mental age is not reported

Global motion
Global motion study with target location as response and motion coherence level as outcome.

Atkinson et al (2003)[19]

					Williams Syndrome [a]	Statistics [d]
n	-	-	-	-	41	
Gender (% male)					-	
Age range in years (mean; *SD*)	4-5.5	5.5-6.9	7-8	10-11	4.75-12.99 (-)	
Mental age years [b]					≥ 4	
Global motion						
Mean motion coherence level % [c] (*SD*)					32 (12)	-
Median motion coherence level % [c] (*SD*)	31	30	24	20	29	
P_{90} motion coherence level% [c]	54	37	30	26	-	

[a] 4 patients were excluded because of the age the criterion; [b] Outcomes of the British Picture Vocabulary Scale were used to assess mental age in patients; [c] Data was extracted from a figure with group results for controls and individual results for patients; [d] Patients results were only compared to p_{90} of controls (percentile 90) of controls: 45% of patients performed worse than p_{90} percentile, if mental age was used for performance evaluations 18% of patients performed worse than p_{90}

Biological motion
Biological motion study with target or non-target as unbiased measure of sensitivity (d') as outcome.

Blake et al (2003)[20]

	Autism	Controls	Statistics
n	12	9	
Gender (% male)			
Age range in years (*SD*)	8-10 (-)	5-10 (8.42; 1.89)	
IQ information	-	-	
Biological motion			
unbiased measure of sensitivity d' (*SD*) [a]	2.52 (0.5)	1.17 (0.7)	$t(19) = 2.68$, p = .02

[a] Data was extracted from a figure with group results.

Excluded studies - Developmental data
Ordered by publication year

Motion-defined form
Motion-defined form study with gap position as response and (weighted) percentage Correct response as outcome.

Schrauf et al (1999)[21]

	Controls								
	4 year olds	5 year olds	6 year olds	7 year olds	8 year olds	9 year olds	10 year olds	11 year olds	12 year olds
n	-	-	-	-	-	-	-	-	-
Age range in years	-	-	-	-	-	-	-	-	-
IQ information	-	-	-	-	-	-	-	-	-
Motion-defined form									
Males									
Mean percentage correct % [ab] (SEM)	67 (7)	67 (7)	67 (8)	69 (9)	72 (3)	75 (2)	78 (3)	80 (3)	81 (4)
Females									
Mean percentage correct % [a]	74 (7)	74 (6)	74 (7)	74 (7)	74 (3)	74 (4)	75 (5)	76 (5)	77 (5)

[a] Data was extracted from a figure with group results; [b] In the age group 4-6 year olds also mean percentage correct % per coherence level was illustrated: 100% coherence 94% (SEM = 1); 50% coherence 90% (SEM = 3); 30% coherence 79% (SEM = 4); 20% coherence 63% (SEM = 5).

Biological motion
Biological motion study with naming and facing direction as response and percentage correct as outcome.

Pavlova et al (2001)[22]

	Controls		
	3 year olds	**4 year olds**	**5 year olds**
n	16	16	16
Gender (% male)	63	56	50
Age range in years (*SD*)	- (3.58; 0.17)	- (4.42; 0.25)	- (5.42; 0.33)
IQ information	-		-
Biological motion			
Naming PLW			
Mean percentage correct %	23	42	100

PLW = point light walker

Global motion
Global motion study with motion direction as response and coherence level (%;(Signal gabors/(Signal gabors + Noise gabors)*100)as outcome.

Ellemberg et al (2004)[23]

	Controls	**Statistics [a]**
n	24	
Gender (% male)		
Age range in years (mean; *SD*)	4.75-5.25 (5.0; -)	
IQ information	-	
Global motion		
Mean motion coherence level % per test condition		
Luminance defined		Age [a]: $F(1, 46) = 24.03$, $p < .01$
speed 1.5 deg/s (*SD*)	24 (20)	Speed: $F(2, 46) = 26.80$, $p < .01$
speed 6 deg/s	7	
speed 9 deg/s	6	
Contrast defined		Age [a]: $F(1, 46) = 27.51$, $p < .01$
speed 1.5 deg/s (*SD*)	36 (29)	Speed: $F(2, 46) = 40.53$, $p < .01$
speed 6 deg/s	8	
speed 9 deg/s	7	

[a] An adult group was included in the original study.

Motion-defined form
Global motion study with motion direction as response and coherence level as outcome. Motion-defined form study with identification as response and minimum dots speed (deg/s) as outcome.

Parrish et al (2005)[24]

	Controls					Statistics [a]
	3-4 year olds	**5-6 year olds**	**7-8 year olds**	**9-10 year olds**	**11-12 year olds**	
n	11-33	11-33	11-33	11-33	11-33	
Gender (% male)	-	-	-	-	-	
Age range in years	-	-	-	-	-	
IQ information	-	-	-	-	-	
Motion perception						
Global motion						MANOVA Age group: $F(10, 130) = 1.37$, *ns*
n	23	23	23	23	23	
Mean coherence level %	33	30	23	24	30	
n	11	11	11	11	11	MANOVA Age group: $F(10, 118) = 2.39$, $p < .05$ [c] ANCOVA with covariate visual acuity (LogMAR) Age group: $F(5, 61) = 3.85$, $p < .05$
Mean D_{max} deg	0.86	0.97	1.05	1.05	1.06	
Motion-defined form						MANOVA Age group: $F(8, 188) = 2.95$, $p < .01$.[b] ANCOVA with covariate visual acuity (LogMAR) Age group: $F(4, 59) = 1.89$, *ns*
n	13	13	13	13	13	
Mean minimum dot speed deg/s (*SD*)	0.28 (0.06)	0.18 (0.03)	0.14 (0.02)	0.09 (0.02)	0.14 (0.04)	

[a] Global motion studies included an adult group. Each age group for the mean coherence level analysis consisted of 12 subjects; [b] Performance of 3-4 year olds was significantly different from other groups (*p*-value not available); [c] Performance of 3-4 and 5-6 year olds was significantly different from adults (*p*-value not available).

Biological motion
Biological motion study with target or non-target as response and percentage correct and number of tolerated noise dots as outcome.

Freire et al (2006)[25]

	Controls		Statistics [a]
	6 year olds	9 year olds	
n	24	24	
Gender (% male)	50	62	
Age range in years (*SD*)	- (6.0; 0.25)	- (9.0; 0.25)	
IQ information	-		
Biological motion			
Correct identification			
Mean percentage correct % (*SD*; range)	95 (-; 90-100)	94 (-; 86-100)	
Mean number of noise dots tolerated (*SD*)	69.26 (12) [c]	77.76 [b] (12) [c]	Age group: $F(2, 69) = 6.00$, $p < .01$ 6 year olds vs. adults: $p < .01$ 9 year olds vs. adults: *ns*

[a] Also an adult group was included in the study; [b] One outliers was replaced by the group mean; [c] Data was extracted from a figure with group results.

Biological motion
Biological motion study with target or non-target as response and reaction time as outcome.

Lichtensteiger et al (2008)[26]

	Controls	Statistics [a]
n	13	
Gender (% male)	62	
Age range in years (*SD*)	- (6.59; 1.2)	
IQ information	-	
Biological motion		Age group: $F(1, 29) = 57.36$, $p < .01$. Children are slower than adults
Target		
Mean reaction time sec (*SD*; range)	1.36 (0.22)	
Non-target		
Mean reaction time sec (*SD*; range)	1.50 (0.25)	

[a] Also an adult group was included in the study.

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