ORIGINAL ARTICLE

Study of auditory and visual perception in relation to spatial orientation in young children

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Abstract

The aim of this longitudinal study is to evaluate spatial orientation in children. The possible relationship between perception (visual and auditory) and spatial orientation will be examined. Other objectives are the investigation of developmental and gender differences concerning spatial orientation. Children were recruited for this study from the last year of nursery school, and were monitored for 7 years. Each year the Piaget test for spatial orientation, the Test of Visual Perceptual Skills for visual perception and the Stambak Rhythm test for auditory perception were administrated. The Piaget test was fairly correlated with the Test of Visual Perceptual Skills and with the Stambak Rhythm test, which indicates that visual and auditory perception are related to spatial orientation. Secondly, a positive evolution of spatial orientation in function of age was found, mainly in the first grades of elementary school. No significant gender differences concerning spatial orientation were noted.

Key Words: Piaget-Head test, Test of Visual Perceptual Skills, Stambak Rhythm test, spatial orientation, perception, development, integration, space, visual, auditory, multisensory, children, gender.

Already during the first years of life, spatial orientation is used to guide our movements. The investigation of aspects related to spatial orientation can lead to useful key concepts concerning children's development. According to Kephart (1960), spatiality develops in the brain. Using sensory perception, humans receive information about the distance between ourselves and an object, and the distance between two objects. Spatial perception is a process that, among others, forms part of spatial cognition, affecting spatial orientation. Spatial perception refers to primary visual, auditory and haptic contact with spatial structures. Spatial cognition includes all the cognitive modalities of the spatial factor, such as spatial memory, thinking and representation. During the first years of life, babies are only able to make use of the first modality because spatial cognition has not yet developed (Kephart, 1960). Starting between the ages of 5 and six years, the productive spatial language, especially the words ”left” and “right” allows successful performance on orientation tasks (Hermer-Vasquez, Moffet, & Munkholm, 2001).

Spatial skills play a key role in many types of reasoning and communication and are important in domains such as mathematics, natural sciences, and engineering (Wright, Thompson, Ganis, Newcombe, & Kosslyn, 2008). Spatial orientation develops as sensory and motor development take place (Simons, 2014). The auditory system, important for spatial recognition, is already functioning prenatally (Gottlieb, 1971). It is generally assumed that besides verbal and non-verbal abilities of the human intelligence also a visual-perceptual component exists. This component means that we experienced through the body, space and time orientation and motor skills, what allows spatial representations (de Groot & Paagman, 2000). Impairments in spatial orientation can so lay the foundations of learning difficulties such as dyslexia, dyscalculia, dysgraphia, and Non-verbal Learning Disabilities (NLD).

The visual system, develops particularly after birth. Between two and five months of age, the baby begins to lift its head; later on, the coordination of muscular work, vision and touch starts to develop. Around 12 months, the child starts to walk and from then, the environment is discovered in a more dynamic way (Simons, 2014). During the first six months of life, a child represents its environment based on visual input. Later, interaction between visual and postural information takes place (Bremner, Holmes, & Spence, 2008). Additionally, there is a change in the child’s point of view. At first, the child localises objects with respect to itself. Later, the child is able to localise objects against a fixed system of reference: first the vertical then the sagittal and finally the horizontal dimension of this system develops. A three dimensional space is formed (Simons, 2014). There is limited information describing the further evolution of spatial orientation in function of age. But there is a great deal of evidence, that information sources are frequently combined to determine behaviour. One of the objectives of this study will be the exploration of this evolution.

Gender differences concerning spatial ability emerge from the age of four and a half. On average, boys are more accurate at spatial tasks (Levine, Huttenlocher, Taylor, & Langrock, 1999). The size of this difference in accuracy depends on the task’s demands (Coluccia & Louse, 2004; Kimura, 1999; Linn & Petersen, 1985; Voyer, Voyer, & Bryden,1995). Small differences were found in simple commonly used tasks. In more difficult tasks, that require a high load of visual spatial working memory, however, clear but more varying differences were observed in favour of boys (Loring-Meier & Halpern, 1999). Males responded more quickly on image generation, maintenance, scanning, and transformation with no between-sex differences in accuracy. They concluded that speed of processing was central to understanding sex differences in visuospatial working memory (Loring-Meier & Halpern, 1999). The sample used in this current study is composed of boys and girls and therefore the exploration of possible gender differences at several points of the development in children will be an objective.

Multisensory integration refers to gathering information from different senses to obtain a better estimation of a specific object or event (Alais & Burr, 2004; Ernst & Banks, 2002). Given the topic of the study, the interaction between the auditory and visual system requires investigation. This interaction takes place among others in the superior colliculus (Stein & Meredith, 1993), which is a structure of the midbrain consisting of different layers. The neurons in the upper layers process visual information, while bimodal neurons in the deeper layers combine visual, auditory and haptic information (Stein, Meredith, &Wallace, 1993). Other regions involved in multisensory integration are the auditory and visual cortex (Foxe, Morocz, Murray, Higgins, javitt & Schroeder, 2000; Martuzzi,et al., 2007; Romei, Murray, Merabet, & Thut, 2007; Shams, Iwaki, Chawla, & Bhattacharya, 2005), the superior temporal sulcus (Barraclough et al., 2005; Benevento, Fallon, Davis, & Rezak, 1977; Bruce, Desimone, & Gross, 1981) and the lateral and ventral intraparietal areas (Lewis & Van Essen, 2000; Linden, Grunewald, & Andersen, 1999). Certain rules need to be followed before interaction can take place. Two stimuli from different modalities need to be presented at the same time (temporal rule) and more or less at the same location (spatial rule) (Stein & Meredith, 1993).

The modalities involved in multisensory integration can facilitate, influence or deceive one another. Lewkowicz and Lickliter (1994) provided evidence of cross-modal facilitation. This process refers to the reinforcement of the response of one stimulus by another (Lewkowicz & Lickliter, 1994; Lickliter, Lewkowicz, & Columbus, 1996; Morrongiello, Fenwick, & Chance, 1998). Audiovisual facilitation is seen in reflexive head and eye movements around eight months of age (Neil, Chee-Ruiter, Scheier, Lewkowicz, & Shimojo, 2006). Around the age of eight years, audiovisual facilitation appears in more complex motor tasks, such as audiovisual detection tasks (Barutchu, Crewther, & Crewther, 2009; Barutchu, Danaher, Crewther, Innes-

Brown, Shivdasani, & Paolini, 2010). Secondly, a cross-modal transfer is often described. Information from one sensory system can be transferred to another (Streri, Gentaz, Spelke, & van de Walle, 2004). For example, a person trained to visually recognise an object will often be able to recognise that object by touch alone (i.e. without seeing it) (Wallraven, Bulthoff, Waterkamp, van dam, & Geissert, 2014; Yildirim & Jacobs, 2013). A third possibility is a multisensory illusory effect, such as attentional capture. Theeuwes, Belopolsky and Olivers (2009) describe attentional capture as the fact that spatial attention can be drawn to a location in space against our will. For example, when you are looking at something, and a loud sound is presented from somewhere else, your attention will be drawn towards this sound. One last important key concept in audio-visual interaction concerning spatial orientation is the ventriloquist effect. This effect suggests that vision dominates audition when the spatial locations of auditory and visual stimuli are in conflict (Warren, Welch, & McCarthy, 1981; Mateeff, Hohnsbein, & Noack, 1985). In this case, the spatial rule for multisensory integration is not met. There is a shift in the perception of an auditory stimulus towards the location of a visual stimulus (Howard & Templeton, 1966; Welch & Warren, 1980; Jack & Thurlow, 1973; Radeau & Bertelson, 1977; Radeau & Bertelson, 1978). The modality specificity hypothesis (Welch & Warren, 1980) explains this effect by suggesting that the sensory modality with the greatest predictive acuity, in this case the visual system, will dominate.

The majority of publications about multisensory integration thus far have involved adults. Therefore, the main objective of this study is to examine multisensory integration – in this case auditory and visual interaction – regarding spatial orientation of children between the ages of 4 and 13 years.

After analysing the literature, an overall hypothesis regarding this subject is formulated: there is a relationship between perception (visual and auditory) and spatial orientation in children. A second hypothesis is that there is a positive evolution of spatial orientation in function of age. The final hypothesis, concerning gender differences in spatial orientation, states that there is a difference between boys and girls; boys score significantly higher on spatial orientation tasks.

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Method

Participants

This longitudinal study examined typically developing children from the last year of nursery school through the sixth grade, from 1995 through 2002. A school in Zoersel (near Antwerp, Belgium) was willing to cooperate. In each subsequent grade, children were included in this study if the scores of all three tests were available. Because some children left the school and new children joined during the various years of the study, the number of children studied varied for each grade. The mean ages by educational level are shown in Table 1. This study will use educational levels rather than chronological age in the further analysis. No exclusion criteria were specified. Eyeglass correction was applied for children who normally wore glasses. Most children came from a family with a higher socioeconomic standard. The parents and the school director signed a written consent form.

Table 1. Mean ages by educational level

Educational level	N total	N boys	N girls	M_{age} (years)	SD_{age}
Preschool	51	24	27	5.49	0.26
1st grade	61	30	31	6.67	0.38
2nd grade	57	26	31	7.57	0.34
3rd grade	54	25	29	8.57	0.37
4th grade	53	21	32	9.66	0.55
5th grade	48	18	30	10.60	0.46
6th grade	27	11	16	11.56	0.26

Materials

Three tests were selected as being relevant for this study. The first, the *Piaget Droite-Gauche test* (Piaget, 1924; Galifret-Granjon, 1966), assesses spatial orientation. This test consists of ten questions, divided into three major parts: 1) the subject points to an area indicated on his or her body (maximum 2 points), 2) the subject points to an area indicated on the examiner's body and (maximum 4 points) 3) the subject must distinguish the relative position between objects (maximum 14 points). It is not a performance test whose reliability can be examined; it only explores whether children have reached a certain stage of development. It clearly assesses left-right orientation in general, and therefore the validity problem is inapplicable (Piaget, 1924; Galifret-Granjon, 1966). Norm scores for this test are available for children from 6 years to 14.5 years of age (Simons, 2014). For the statistical analysis, the total score of this test (TSP: Total Score Piaget) (sum of the subtests, 0 - 20 points) will be used.

The second test used is the *Test of Visual-Perceptual Skills* (TVPS) (Gardner, 1982). A newer version, the TVPS-3, was recently published (Martin, 2006), however, the data available for this study were recorded using the old version. The weaknesses and strengths of visual perception in children are measured using non-motor tasks. This test consists of seven subtests: visual perception, visual discrimination, visual memory, visual-spatial relationships, visual-form constancy, visual-sequential memory, visual figure ground and visual closure. In total, the test contains 112 items with an increasing order of difficulty. The internal consistency for the test in total equals α = .96 (excellent); at item level, α varies from .75 to .87 (good). The test-retest reliability amounts r = .97 for the entire test; for the subtests, this varies between .34 and .81. Item validity is achieved by incorporating items of increasing difficulty. The different items have been created in function of important factors of visual perception. The inter-subtest correlations range from .18 to .40; the subtest total correlations range from .54 to .65. Criterion-related validity is measured by correlating the TVPS with other tests (Chronological age, Picture Completion subtest of the Wechlers Preschool and Primary Scale of Intelligence and the Wechlers Intelligence Scale for Children-Revised, Bender Visual-Motor Gestalt Test and the Developmental Test of Visual-Motor Integration). The ages of the norming group range from 4 years to 12 years 11 months (Gardner, 1982). For the TVPS, a total raw score (TSTVPS: Total Score Test of Visual Perceptual Skills) (0 - 133) is calculated for the statistical analysis, using the scores from the different subtests.

The *Stambak rhythm test* (Zazzo et al., 1958), which examines auditory perception, is the third test added to the study. It consists of three major parts, but this study only uses the third part in which the subject reproduces 21 given rhythmic symbols, with increasing order of difficulty. A high raw score indicates high number of mistakes. Information concerning reliability and validity is not available (Zazzo et al., 1958). Norm scores are calculated for children from 6 to 15 years of age (Simons, 2014). The raw score of this test (TSS: Total Score Stambak) (number of failures, 0 - 21) will be incorporated in the statistical analysis.

Procedure

All three tests were administered individually each year by trained examiners, where possible on the same day. The Piaget test (1966), the Test of Visual Perceptual Skills (1982) and the Stambak Rhythm test: third part (1958) were carried out in Dutch, the officially spoken language in Zoersel, Antwerp. The tests were administered in random order, so that fatigue and other confounding factors had little influence on the test results. The appropriate guidelines were followed for each test. None of the tests make use of a time limit, the aim, however, is for children to respond as quickly as possible (Gardner, 1982; Galifret-Granjon, 1966; Piaget, 1924; Zazzo et al., 1958). The total testing time for the Piaget test is 5 minutes. The children are given one attempt to provide the right answer to each question (Simons, 2014). For the TVPS, the testing time varies – according to the age of the child – from 30 to 45 minutes. For each subtest, two trial attempts are allowed. During the actual test, if the child answers wrongly three times, the examiner continues to the next subtest (Gardner, 1982). The Stambak Rhythm test first examines if the child understands the given rhythmic symbols. If so, the child may proceed to the reproduction part. After the first 12 rhythmic structures, scoring is stopped after three consecutive errors. The quality of the reproduction is evaluated (Zazzo et al., 1958).

Statistical analysis

For this statistical analysis, “Statistica 12” was used. For all tests, a significance level of α=.05 was determined (Thomas, Nelson, & Silverman & Silverman 2005). The Kolmogorov-Smirnov test was used to investigate the normal distribution of the entire test group. Pearson Product-Moment correlations (Pearson r) were determined to evaluate the interaction between the results of the three different tests obtained over a seven-year period. A Multi-factor Analysis of Variance (MANOVA) was used to evaluate the evolution of spatial orientation and to detect possible gender differences. Independent variables were educational level and gender, whereas the Total Score Piaget Test (TSP), the Total Score Test of Visual Perceptual Skills (TSTVPS) and the Total Score Stambak Rhythm Test (TSS) were the dependent variables. In order to detect main and interaction effects, the MANOVA calculated a Wilk's Lambda (Λ), which in turn was transformed to an F-value and finally converted to a p-value. Additionally, a univariate analysis was conducted for each dependent variable. Sheffé post hoc analyses were carried out in order to detect which scores differed significantly.

Results

Correlation visual perception, auditory perception and spatial orientation

A fair correlation was found between the Piaget test and the TVPS ($r = .35$, $p < 0.05$), and between the Piaget test and Stambak Rhythm test ($r = -.37$, $p < 0.05$). The results of the TVPS and the Stambak rhythm test were moderately correlated ($r = -.58$, $p < 0.05$) (Portney & Watkins, 2008). The negative correlations were due to the fact that a high score on the Stambak Rhythm test was a less good result (the number of failures). High scores on the Piaget test and the TVPS referred to positive results.

Evolution in spatial orientation and gender differences

No significant interaction effect was found for both gender and educational level (Wilk's Lambda = 0.779, $F = 1.30$, $p = 0.071$), but significant main effects presented themselves (Wilk's Lambda = 0.923, $F = 2.50$, $p = 0.005$; Wilk's Lambda = 0.039, $F = 22.10$, $p = 0.000$).

A univariate analysis of educational level and gender was performed for all three tests separately (Table 2 and 3). For total score Piaget, the effect of educational level did reveal a significant difference ($p < 0.05$) (Table 2). No statistically significant effect for gender was found ($p > 0.05$) (Table 3). For total score TVPS and total score Stambak, a significant effect was found for both gender and educational level ($p < 0.05$) (Table 2 and 3).

Table 3. Univariate results for Gender

	Boys		Girls		F-value (11; 327.00)[a]	p-value
	M	SD	M	SD		
Test of Piaget	14.44	5.34	15.89	5.09	3.468	0.063
Test of Visual Perceptual Skills	75.70	22.77	83.32	19.48	16.07	0.000
Stambak Rhythm Test	7.28	4.78	6.04	4.53	4.542	0.034

Note. [a] Effect df; Error df

Post hoc analyses showed that the significant differences for educational level were more prominent in the lower groups (pre-school, first grade and second grade) as opposed to the higher groups (fourth, fifth and sixth grade) for total score Piaget. A similar trend was observed in the cases of total score TVPS and total score Stambak. More detailed documentation is provided in Table 2.

Table 2. Univariate results for Educational level

	Preschool A		1st grade b		2nd grade c		3rd grade d		4th grade e		5th grade f		6th grade g		F-value (66; 1755.18)[a]	p-value	Sheffé Post Hoc
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD			
Test of Piaget	10.35	3.96	12.20	4.64	15.16	5.84	16.30	4.49	18.15	3.43	17.64	4.26	19.63	1.24	27.119	0.000	a < c, d, e, f, g b < c, d, e, f, g c < e, g
Test of Visual Perceptual Skills	45.18	15.71	71.62	13.38	78.77	13.20	86.02	14.43	91.98	11.91	97.25	9.80	100.52	7.99	104.18	0.000	a < b, c, d, e, f, g b < d, e, f, g c < e, f, g d < f, g
Stambak Rhythm Test	11.94	4.07	9.93	3.62	8.03	3.54	4.65	3.08	3.80	2.55	3.02	2.32	1.55	1.65	67.669	0.000	a > c, d, e, f, g b > d, e, f, g c > d, e, f, g

Note. [a] Effect df; Error df

Discussion

The overall hypothesis of this study stated that there is a relation between perception (visual and auditory) and spatial orientation. The data confirmed 'the multisensory hypothesis': a significant correlation was found between the test scores of the Piaget test on one the hand and the Test of Visual Perceptual Skills and the Stambak Rhythm test on the other (r:.35, r:-.37).

However, a correlation coefficient of .58 was found for the intercorrelation between the test scores of the Test of Visual Perceptual Skills and the Stambak Rhythm test. This implies that auditory and visual perception are more strongly related to each other than spatial orientation is related to visual or auditory perception. Because this main research question has – to our best knowledge – never been investigated, there are no results in the literature to serve as comparison. On the other hand the correlation does not mean that there is causality.

Secondly, it was hypothesised that a positive evolution in spatial orientation as a function of age can be seen. The results of the three tests improved gradually with age. In general, only limited information on the evolution in spatial orientation is available. According to Piaget and Inhelder (1948), the development of spatial ability mainly takes place between the ages of 5 and 9-10 years. Major improvements in spatial knowledge can be found between the ages of 6 and 9 (Allen & Ondracek, 1995). In this study, significant differences between the test scores of the educational levels were more prominent in the lower groups (pre-school, first grade and second grade) as opposed to the higher groups (fourth, fifth and sixth grade). This may imply that the improvement in spatial orientation mainly takes place in the first grades of primary school. The fact that this study made use of educational levels instead of chronological ages in evaluating the evolution of spatial orientation, may have influenced the results. For students who had to repeat a year, the chronological age may have been a better alternative for this evaluation. On the other hand, their lagging behind in the area of spatial orientation may partially contribute to the need to repeat a year (National Research Council, 2006).

Finally, it was expected that the Piaget test results of boys would differ significantly from those of girls. According to our hypothesis, boys would score higher than girls on spatial orientation tasks. Our data analysis revealed significant differences between the test scores of boys and girls on the test of Visual Perceptual Skills and the Stambak Rhythm test. On the contrary, no significant influence of gender on spatial orientation test scores, as measured by the Piaget test, was found. Gender differences in spatial ability, however, have been well documented (Coluccia & Louse, 2004; Halpern, 2007; Kimura, 1999; Levine, Vasilyeva, Lourenco, Newcombe, & Huttenlocher, 2005; Voyer et al., 1995). Early research on this topic noted higher scores for males on standard tests of spatial ability (Maccoby & Jacklin, 1974). But more recent research reported that gender differences already emerge in pre-school and at the beginning of the first grade (Levine et al., 1999). The reason why this study showed no significant gender differences concerning spatial orientation may have something to do with the sample size, which is rather small. The average number of boys that participated in this study was 22; for girls, the average was 28. Loring-Meier and Halpern (1999) found clear but varying differences in favour of boys for difficult spatial orientation tasks that place a high load on visual-spatial working memory.

The Piaget test used in this study contained only simple spatial orientation tasks, which did not really make use of visual-spatial working memory. This may be another reason why this study indicated no significant gender differences. However, the authors mentioned above (Loring-Meier & Halpern, 1999) noted differences even in simple, commonly performed tasks.

Spatial ability, essential to mathematics, scientific thinking, problem solving, … (Delgado & Prieto, 2004), is not commonly assessed and taught at school in a way that would allow it to influence the future educational plans of students (Webb, Lubinski, & Benbow, 2007). The results of this research contribute to knowledge of spatial development in normally developing children. Since there is very little existing research on this topic, a better understanding of spatial orientation in general and the role played by auditory and visual perception could make an important contribution. Studying this relationship in greater detail might reveal one of many reasons for deviation from the norm concerning spatial orientation tasks and mathematical tasks. Cheng and Mix (2014) conclude that spatial ability and mathematics rely on the same cognitive processes. Many studies state that space and mathematics are already related in the early grades, and that an early intervention is needed for closing achievement gaps in mathematics (Duncan et al., 2007; Jordan, Kaplan, Ramineni, & Locuniak, 2009; Klibanoff, Levine, Huttenlocher, Vasilyeva, & Hedges, 2006; Saxe, 1987; Starkey, Klein, & Wakely, 2004). A possible intervention for problems in spatial ability and mathematics is spatial training (Cheng & Mix, 2014). In fact, the integration of spatial training into the elementary mathematics curriculum is recommended by the National Council of Teachers of Mathematics (2010). However, many authors conclude that the effects of spatial training are task-specific and context-bound (National Research Council, 2006; Wright, et al., 2008).

Caution should be exercised when extrapolating the findings of this current study. Further research is needed to confirm the findings. Studies that use other tests to examine the relation of auditory and visual perception with respect to spatial orientation are advisable. In addition, the investigation of spatial orientation – and the role played by auditory and visual perception – in children with a deviant development might be interesting.

Possible limitations of this study include the rather small sample size and the lack of verification of whether the socioeconomic status of the children influenced the test results. Since most children come from a family with a higher socioeconomic standard, this study chose to ignore this potential confounding effect. Since the Piaget test, the Test of Visual Perceptual Skills and the Stambak Rhythm test are correlated, it is concluded that visual and auditory perception are related to spatial orientation. With the Stambak Rhythm test the founded correlation was negative due to the fact that to calculate the raw score of the Stambak Rhythm test the number of mistakes were used. A second conclusion is that spatial orientation evolves in function of age. In this study, no differences concerning spatial orientation were noted between boys and girls. Overall, more research on this topic is needed.

References

Alais, D., & Burr, D. (2004). The ventriloquist effect results from near-optimal bimodal integration. *Current Biology, 14*, 257-262.

Allen, L., & Ondracek, P. (1995). Age-sensitive cognitive abilities related to children's acquisition of spatial knowledge. *Developmental Psychology, 31*, 934-945.

Barraclough, N. E., Xiao, D. K., Baker, C. I., Oram, M. W., & Perrett, D. I. (2005). Integration of visual and auditory information by superior temporal sulcus neurons responsive to the sight of actions. *Journal of Cognitive Neuroscience, 17*(3), 377-391.

Barutchu, A., Crewther, D.P., & Crewther S.G. (2009). The race that precedes coactivation: development of multisensory facilitation in children. *Developmental Science, 12*, 464-473.

Barutchu, A., Danaher, J., Crewther, S.G., Innes-Brown, H., Shivdasani, M.N., & Paolini, A.G. (2010). Audiovisual integration in noise by children and adults. *Journal of Experimental Child Psychology, 105*, 38-50.

Benevento, L. A., Fallon, J., Davis, B. J., & Rezak, M. (1977). Auditory–visual interaction in single cells in cortex of superior temporal sulcus and orbital frontal cortex of macaque monkey. *Experimental Neurology, 57*(3), 849-872.

Bremner, A.J., Holmes, N.P., & Spence, C. (2008). Infants lost in (peripersonal) space? *Trends in Cognitive Sciences, 12*, 298-305.

Bruce, C., Desimone, R., & Gross, C. G. (1981). Visual properties of neurons in apolysensory area in superior temporal sulcus of the macaque. *Journal of Neurophysiology*, *46*(2), 369-384.

Burr, D., & Gori, M. (2012). *The Neural Bases of Multisensory Processes*. Boca Raton, FL: CRC Press.

Cheng, Y., & Mix, K. S. (2014). Spatial training improves children's mathematics ability. *Journal of cognition and development*, *15*(1), 2-11.

Coluccia, E., & Louse, G. (2004). Gender differences in spatial orientation: a review. *Journal of Environmental Psychology, 24*, 329-340.

Delgado, A. R., & Prieto, G. (2004). Cognitive mediators and sex related differences in mathematics. *Intelligence, 32,* 25-32.

De Groot, R., & Paagman, C.J. (2000). *Kinderen met leer- en gedragsproblemen.* Amsterdam: Boom.

Duncan, G. J., Dowsett, C. J., Claessens, A., Magnuson, K., Huston, A. C., Klebanov, P., & Japeli, C. (2007). School readiness and later achievement. *Developmental Psychology, 43*, 1428-1446.

Ernst, M.O., & Banks, M.S. (2002). Humans integrate visual and haptic information in a statistically optimal fashion. *Nature*, *415*, 429-433.

Foxe, J. J., Morocz, I. A., Murray, M. M., Higgins, B. A., Javitt, D. C., & Schroeder, C. E. (2000). Multisensory auditory-somatosensory interactions in early cortical processing revealed by high-density electrical mapping. *Cognitive Brain Research*, *10*(1–2), 77-83.

Gardner, M.F. (1982). *Test of Visual-perceptual skills (non-motor), Manual*. San Francisco, California: Health Publishing Company.

Gori, M., Sandini, G., & Burr, D. (2012). Development of Visuo-Auditory Integration in Space and Time. *Frontiers in Integrative Neuroscience*, *6*, 77.

Gottlieb, G. (1971). *Development of species identification in birds: An inquiry into the prenatal determinants of perception*. Chicago: Univ. of Chicago Press.

Halpern, D. F. (2007*).* Science sex and good sense: Why women are underrepresented in some areas of science and math. In Ceci, S. J. & Williams, W. M. (2007). *Why aren't more women in science? Top researchers debate the evidence*, 121-130. Washington, DC: American Psychological Association.

Heilman, K. M., Bowers, D., Valenstein, E., & Watson, R. T. (1987). Hemispace and hemispatial neglect. *Neurophysiological and neuropsychological aspects of spatial neglect, 45*, 115-150.

Hermer-Vasquez, L., Moffet, A., & Munkholm, P. (2001). Language, space, and the development of cognitive flexibility in humans: The case of two spatial memory tasks. *Cognition, 79*, 263-299.

Howard, I.P., & Templeton, W.B. (1966). *Human Spatial Orientation.* New York: Wiley.

Jack, C.E., & Thurlow, W.R. (1973). Effects of degree of visual association and angle of displacement on the ‘‘ventriloquism” effect. *Perceptual Motor Skills*, *37*, 967-979.

Jordan, N. C., Kaplan, D., Ramineni, C., & Locuniak, M. N. (2009). Early math matters: Kindergarten number competence and later mathematics outcomes. *Developmental Psychology, 45*, 850-867.

Kephart, N.C. (1960). *The slow learner in the Classroom.* Columbus: Merrill.

Kimura, D. (1999). *Sex and cognition.* Cambridge, MA: MIT Press.

Kinsbourne, M. & Jeannerod, M. (ed.) (1987). Mechanisms of unilateral neglect. *Neurophysiological and neuropsychological aspects of spatial neglect*, 69-86.

Klibanoff, R. S., Levine, S. C., Huttenlocher, J., Vasilyeva, M., & Hedges, L. V. (2006). Preschool children’s mathematical knowledge: The effect of teacher ‘math talk’. *Developmental Psychology*, *42*, 59-69.

Koelewijn, T., Bronkhorst, A., & Theeuwes, J. (2010). Attention and the multiple stages of multisensory integration: A review of audiovisual studies. *Acta Psychologica*, *134*, 372-384.

Levine, S. C., Huttenlocher, J., Taylor, A., & Langrock, A. (1999). Early sex differences in spatial skill. *Developmental Psychology*, *35*, 940-949.

Levine, S. C., Vasilyeva, M., Lourenco, F., Newcombe, N.S., & Huttenlocher, J. (2005). Socioeconomic status modifies the sex difference in spatial skill. *Psychological Science*, *16*, 841-845.

Lewis, J. W., & Van Essen, D. C. (2000). Corticocortical connections of visual, sensorimotor, and multimodal processing areas in the parietal lobe of the macaque monkey. *Journal of Comparative Neurology*, *428*(1), 112-137.

Lewkowicz, D.J., & Lickliter, R. (1994). *The development of intersensory perception: Comparative perspectives.* Hillsdale, NJ: Lawrence Erlbaum Associates Inc.

Lickliter, R., Lewkowicz, D.J., & Columbus, R.F. (1996). Intersensory experience and early perceptual development: The role of spatial contiguity in bobwhite quail chicks' responsiveness to multimodal maternal cues. *Developmental Psychobiology*, *29*, 403-416.

Linden, J.F., Grunewald, A., & Andersen, R.A. (1999). Responses to auditory stimuli in macaque lateral intraparietal area II. Behavioral modulation. *Journal of Neurophysiology*, *82,* 343-358.

Linn, M. C., & Petersen, A. C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Development*, *56*, 1479-1498.

Loring-Meier, S., & Halpern, D. (1999). Sex differences in visuospatial working memory: Components of cognitive processing. *Psychonomic Bulletin and Review*, *6*, 464-471.

Mateeff, S., Hohnsbein, J., & Noack, T. (1985). Dynamic visual capture: apparent auditory motion induced by a moving visual target. *Perception, 14*, 721-727.

Martuzzi, R., Murray, M. M., Michel, C. M., Thiran, J. P., Maeder, P. P., Clarke, S., et al. (2007). Multisensory interactions within human primary cortices revealed by BOLD dynamics. *Cerebral Cortex, 17*, 1672-1679.

Morrongiello, B.A., Fenwick, K.D., & Chance, G. (1998). Cross-modal learning in newborn infants: Inferences about properties of auditory-visual events. *Infant Behavior and Development, 21,* 543-554.

National Research Council. (2006). Learning to think spatially: Geographic Information Systems (GIS) as a support system in the K–12 curriculum. Washington, DC: National Academies Press.

Neil, P.A., Chee-Ruiter, C., Scheier, C., Lewkowicz, D.J., & Shimojo, S. (2006). Development of multisensory spatial integration and perception in humans. *Developmental Science, 9*, 454-464.

Piaget, J. (1924). *Le jugement et le raisonnement chez l'enfant*, 130-141. Neuchâtel: Delachaux et Niestlé.

Piaget, J. & Inhelder, B. (1948). *La Representation de l'Espace chef l'Enfant*. Paris: Presses Universitaires de France.

Portney, L. G., & Watkins, M. P. (2008). *Foundations of Clinical Research: Applications to Practice (3rd Edition).* USA: Pearson Education.

Radeau, M., & Bertelson, P. (1977). Adaptation to auditory-visual discordance and ventriloquism in semirealistic situations. *Perception & Psychophysics, 22*, 137-146.

Radeau, M., & Bertelson, P. (1978). Cognitive factors and adaptation to auditory-visual discordance. *Perception & Psychophysics, 23*, 341-343.

Recanzone, G. (2009). Interactions of auditory and visual stimuli in space and time. *Hearing Research, 258*, 89-99.

Romei, V., Murray, M. M., Merabet, L. B., & Thut, G. (2007). Occipital transcranial magnetic stimulation has opposing effects on visual and auditory stimulus detection: Implications for multisensory interactions. *Journal of Neuroscience, 27*(43), 11465-11472.

Saxe, G. B. (1988). Linking language with mathematics achievement: Problems and prospects. In Cocking, R. & Mestre, J. (1988). *Linguistic and Cultural influences on Learning Mathematics.* NY: Erlbaum Associates.

Shams, L., Iwaki, S., Chawla, A., & Bhattacharya, J. (2005). Early modulation of visual cortex by sound: An MEG study. *Neuroscience Letters, 378*(2), 76-81.

Simons, J. (2014). *Introductie tot de psychomotoriek*. Antwerpen/Apeldoorn: Garant.

Stambak, M. (1966). Une éprouve de pointillage. In Zazzo, R. (1958). *Manuel pour l'examen psychologique de l'enfant*. Neuchâtel: Delachaux et Niestlé.

Stambak, M. (1960). *Trois épouvres de rythme*. Neuchâtel: Delachaux et Niestlé.

Starkey, P., Klein, A., & Wakeley, A. (2004). Enhancing young children's mathematical knowledge through a pre-kindergarten mathematics intervention. *Early Childhood Research Quarterly, 19*, 99-120.

Stein, B.E., Meredith, M.A., & Wallace, M.T. (1993). The visually responsive neuron and beyond: multisensory integration in cat and monkey. *Progress in Brain Research, 95,* 79–90.

Streri, A., Gentaz, E., Spelke, E., & van de Walle, G. (2004). Infants' haptic perception of object unity in rotating displays. *Quarterly Journal of Experimental Psychology A, 57*, 523-538.

Takio, F., Koivisto, M., Tuominen, T., Laukka, S. J., & Hämäläinen, H. (2013). Visual rightward spatial bias varies as a function of age. *Laterality, 18*(1), 44-67.

Theeuwes, J., Belopolsky, A., & Olivers, C. N. (2009). Interaction between working memory, attention and eye movements. *Acta Psychologica, 132* (2), 106-114.

Thomas, J. R., Nelson, J. K., & Silverman, S. J. (2005). *Research Methods in Physical Activity, fifth edition.* Champagin, Illinois: Thomson-Shore, Inc.

Tzuriel, D., & Egozi, G. (2010). Gender differences in spatial ability of young children: the effects of training and processing strategies. *Child Development*, *81,* 1471-1430.

Voyer, D., Voyer, S., & Bryden, M. P. (1995). Magnitude of sex differences in spatial abilities: A meta-analysis and consideration of critical variables. *Psychological Bulletin*, *117,* 250-270.

Wallraven, C., Bulthoff, H. H., Waterkamp, S., van Dam, L., & Geissert, N. (2014). The eyes grasp, the hands see: Metric category knowledge transfers between vision and touch. *Psychonomic Bulletin & Review*, *21*(4), 976-985.

Warren, D. H., Welch, R. B., & McCarthy, T. J. (1981). The role of visual-auditory "compellingness" in the ventriloquism effect: implications for transitivity among the spatial senses. *Perception & Psychophysics*, *30*, 557-564.

Webb, R. M., Lubinski, D., & Benbow, C. P. (2007). Spatial ability: A neglected dimension in talent searches for intellectually precocious youth. *Journal of Educational Psychology, 99*, 397-420.

Welch, R.B., & Warren, D.H. (1980). Immediate perceptual response to intersensory discrepancy. *Psychological Bulletin*, *88*, 638-667.

Wright, R., Thompson, W. L., Ganis, G., Newcombe, N. S., & Kosslyn, S. M. (2008). Training generalized spatial skills. *Psychonomic Bulletin & Review, 15*, 763-771.

Yildirim, I. & Jacobs, R. A. (2013). Transfer of object category knowledge across visual and haptic modalities: Experimental and computational studies. *Cognition, 126*, 135-148.

Zazzo, R., Galifret-Granjon, N., Hurtig, M.C., Mathon, T., Pêcheux, M.G., Santucci, H. & Stambak, M. (1958). *Manuel pour l'examen psychologique de l'enfant.* Neuchâtel: Delachaux et Niestlé.