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Review article

Measuring spatial navigation during locomotion in children: A systematic review

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ABSTRACT

Background: Spatial navigation allows us to move around our environment, walking being the most advanced form of human locomotion. Over the years, a range of tools has been developed to study spatial navigation in children. *Aim.* To describe the role of locomotion during the assessment of spatial navigation in children, providing an overview of the instruments available for assessing spatial navigation in typically developing children and those with neurodevelopmental disorders. *Methods and Procedures.* A systematic search was performed in six electronic databases between December 2022 and February 2023, then updated in July 2023. Cross-sectional and observational studies were included. *Outcomes and results.* Of the 3,385 studies screened, 47 were selected for this review. Five studies described the influence of locomotion on spatial navigation, and seven studies included locomotion as an explanatory variable in this area. Most studies focused on children from five to twelve years old, whereas only nine were centred on infants and preschoolers. Just eight assessed spatial abilities in individuals with neurodevelopmental disorders. *Conclusions and implications.* Children with or at risk of neurodevelopmental impairments show poorer spatial navigation skills. Having the choice to actively explore the space is more important than the way they locomote. It is necessary to have tools to assess spatial navigation during locomotion early in infancy.

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What does this paper add?

This is the first systematic review that synthesises and analyses the role of locomotion in spatial navigation across the different tools and tasks used with typically developing children and children with neurodevelopmental impairments. Although all related studies include the use of locomotion, only a handful of them specifically analyse the influence of locomotion or include locomotor variables as measurement outcomes. A key factor for the optimal development of spatial navigation in children is facilitating active and self-initiated exploration from early childhood in familiar and unfamiliar environments, using strategies such as observation training or motivational tasks. There is a need for studies assessing spatial navigation and the influence of locomotion in children, specifically in children with neurodevelopmental disorders and early infancy. The information provided in this paper will give a wide perspective of spatial navigation, including some practical recommendations for clinical and future research in this field.

1. Introduction

Children's development involves active exploration of the surrounding environment. In their seminal work, Piaget and Inhelder (1956) [1] highlighted how infants and young children perceive their environment in relation to their bodies using the "three mountains" task. They also unveiled the challenges faced by children under the age of nine or ten: they often exhibit egocentrism and a lack of projective spatial representations. Furthermore, Piaget proposed that it is not until around nine or ten years of age that children typically begin to demonstrate the use of coordinate systems to organise their understanding of the spatial world and its navigation. In particular, spatial navigation allows children to perform goal-oriented locomotion (or functional locomotion) through the surrounding space and relies on a balanced effort between cognitive and sensorimotor systems [2] including allocentric and egocentric representations, which develop in parallel during infancy. The egocentric representation relies on subject-to-object relationships and allows body-centred representations to be generated. It is crucial for visuomotor control during the planning and execution of an action within the environment [3]. Conversely, the allocentric representation lies in world-based coordinates and object-to-object relationships, which are independent from the subject's point of view [4].

1.1. Strategies and tools to assess spatial memory and spatial orientation in children

Topographical or spatial memory is a critical factor of spatial cognition which enables us to navigate our surroundings, recognise spatial layouts effortlessly, orient ourselves in familiar environments and remember the primary cues that help us to navigate successfully [5].

The main strategies used to assess spatial memory in children are based on memorising the specific location of a hidden reward, a span, or a path. Examples of these are the Radial Arm Maze (RAM) [6] and the Kiel Locomotor Maze (KLM) [7,8]. Spatial memory assessments that measure spatial spans or paths, such as the Walking Corsi Test (WalCT) [9] and the Magic Carpet (MC) [10] are commonly used and require participants to reproduce a sequence on nine squares placed on the floor.

Studies on spatial orientation in children focus on how changes in the environment affect children's capacity to reorient themselves after being blindfolded [11–13]. It is recognised that self-movement is relevant for orientation, but how locomotion variables in young children with and without neurodevelopmental disorders (NDD) can influence navigation outcomes has not been comprehensively analysed.

1.2. Assessing perceptive-motor strategies in spatial navigation in children with neurodevelopmental disorders

Research on the assessment of multisensory integration in self-motion, referred to as path integration, is scarce [2]. The role of path integration in spatial navigation could be crucial when studying children with perceptive-motor difficulties such as Cerebral Palsy (CP) [14]. Children with CP show difficulties in elaborating trajectories, mainly due to impairments in gait speed, stabilisation, head and gaze anticipation, and coordination between head and trunk [15–18]. In addition, perceptual alterations can lead to difficulties in planning and guiding the motor behaviour in an organised way and changing the frame of reference from a body-centred one to one centred on external space [19–21]. Impact on spatial navigation performance has been also described in other populations at risk of NDD disorders, such as premature babies or children with problems of sustained attention, cognitive flexibility, and visuomotor and visuospatial memory [22–26].

Not only children with or at risk of motor disorders have difficulties related to spatial navigation, but also children with other NDDs such as Williams syndrome (WS) or Down syndrome (DS). They also show impairments in coding and updating spatial relationships between objects and their own body [27–29]. All these difficulties impact spatial orientation and spatial memory, reducing their capacity to explore their environment [30–33] and producing a vicious circle in which spatial navigation is not experienced. Consequently, this ability does not follow the usual stages of development.

The displacement of the body using internal and external inputs to move through space and reach a target is known as functional locomotion. It develops early on when children start crawling and improves when they start walking [34–36].

The main objective of this systematic review is to provide a comprehensive overview of the role of locomotion in tassessing spatial navigation in children. A secondary objective is to describe the different instruments available for assessing spatial navigation during walking locomotion in children, describing the assessment characteristics and spatial outcomes in children with NDD and in TD children.

2. Method

2.1. Study selection and data collection

This systematic review was reported following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) 2020 guideline [37]. The meta-research project was registered in PROSPERO (International Prospective Register of Systematic Reviews) and can be accessed online at [MASKED].

2.2. Eligibility criteria

The inclusion criteria were as follows: a) Children were one to twelve years old and with and without NDD; b) Measurements were standardised tests or tasks to assess spatial navigation during walking locomotion in both real and virtual environments; c) The studies

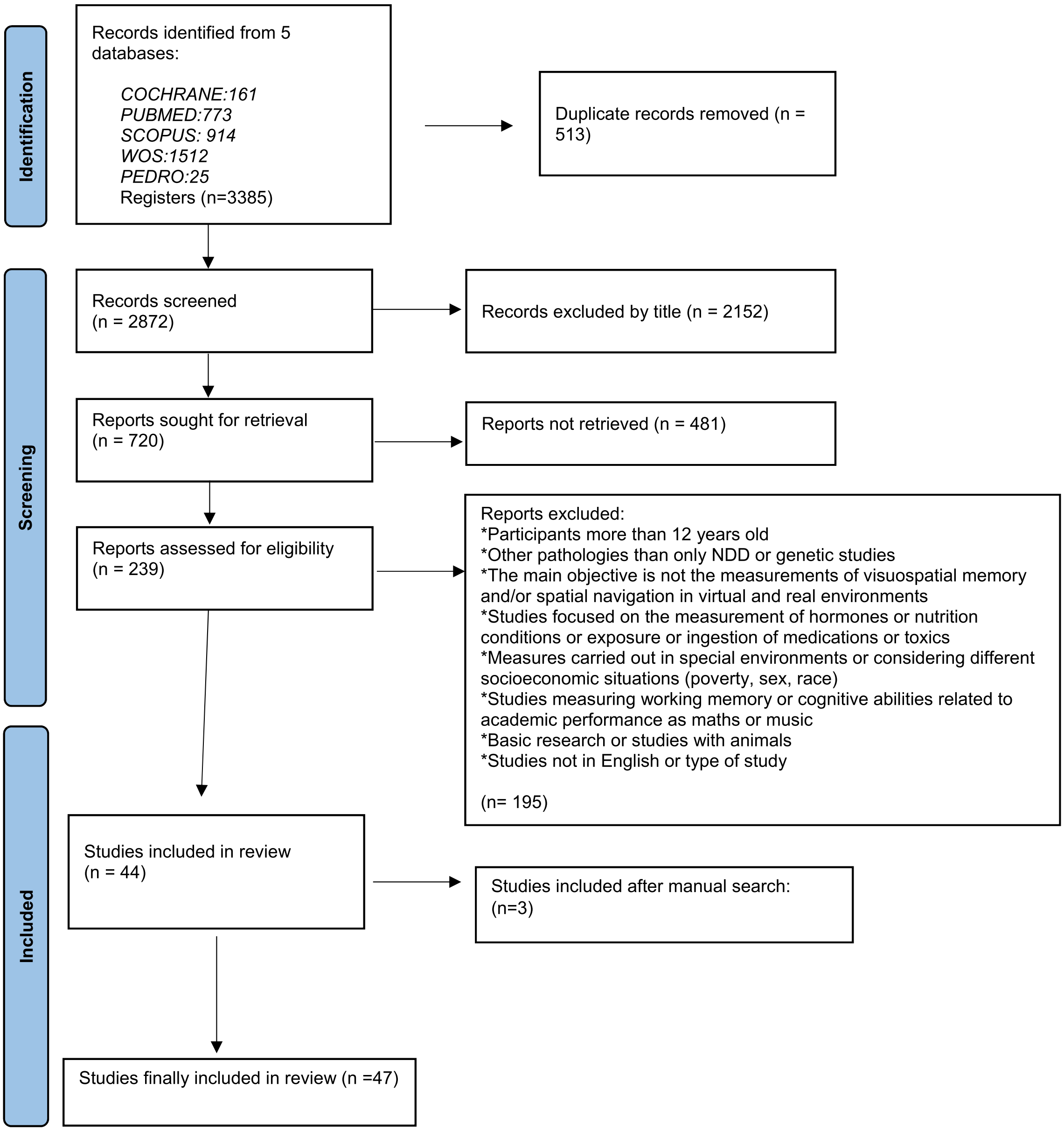

Fig. 1. Preferred reporting items for systematic reviews and meta-analyses (PRISMA) flowchart of information through the different phases of the systematic review. The figure maps out the number of records identified, included, and excluded, and the reasons for exclusions. From Page et al., 2021.

Table 1
Assessment descriptions and characteristics.

Test or task	Studies	Mean age (in years)	Sample size	Type of participants	Aspects related to locomotion	Locomotion as a measurement variable	Summary of results
Visuo-spatial memory tests							
ASRM	[40]	6.9	97	TD	_	__	Visuospatial short-term memory significantly improved (8–9 years old)
	[41]	6.84	76	TD	_	__	5–6-year-old children were able to locate one object between two locations and/or two objects among four locations without environmental cues
Floor matrix task	[33]	5.49 12.72	30 30	TD DS*	_	__	Worse in the map task, DS individuals showed a lower span than TD children
WalCT	[42]	7.3	268	TD	_		Visuospatial competence develops first in peripersonal space and later in extra-personal space.
	[43]	8.5	81	TD	_		___
	[44]	10.5	120	TD	_		Topographical working memory increases as children get older
	[45]	11.9 10.6 9.9	31 10 120	MMC AMC TD	Type of mobility (walking indoors, outdoors or using a wheelchair) is a comparison criterion	__	The MMC group had a significantly lower span than the TD children. Children able to walk outdoors, despite motor disability, had a higher span.
	[46]	11.53 9.89	40 120	CP TD	Level of gross motor function is a comparison criterion	__	Children with GMFCS levels II and III performed significantly worse than TD children. Those with GMFCS level I performed similarly to the TD group. Span was related to prematurity and visuospatial competence.
	[17]	11.53 9.89	40 31 18 120	CP SBORT/ PERI TD	Childrens' everyday mobility is a comparison criterion	__	The WalkOUT group had a longer span than WalkIN in and WalkNO. TD, SB and OR/PERI disability children had a longer span than the CP children.
	[47]	9 9	15 15	ADHD-C TD	__	__	The ADHD-C group had a significantly higher number of perseverative errors than TD. The TSTM, TL, repetition number task during the TL task was lower in the ADHD-C group. The topographical delayed recall (reproduction after 5 min) was not affected.
AWalCT TWalCT	[26]	2.4 2	20 27	TD PT	__	__	At two years old children showed topographical memory. Span is better with age and in TD children. Preterm children present more difficulties initiating tasks, which are related to attention.
MC	[18]	8.5 9.5	91 22	TD CP	Errors related to gross motor function		The TD group span was significantly higher than the CP one with independent walking. No significant differences according to the type of CP.

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Table 1 (*continued*)

Test or task	Studies	Mean age (in years)	Sample size	Type of participants	Aspects related to locomotion	Locomotion as a measurement variable	Summary of results
	[10]	8.97	91	TD	__	Distance travelled, latency and the sum of rotations	The span sequence complexity and distance, and rotational difficulty (updating angles) had a negative effect on navigation. The influence of updating angles decreases with age.
	[48]	8.5 8.8	91 17	TD CP	Differences between children with locomotor impairments and TD children	__	The span did not differ between groups.
Spatial memory task	[49]	10.5	16	TD	Comparison with locomotor experience during the test, with constant updates of the body position		Navigating in the target fields required constant updates of the body position. The position of targets disturbed memory performance more than learning a path standing without moving.
VC_TM	[50]	9.8 10	22 1	ADHD-C TD	__	Trunk and head position and rotation, trunk and head velocity, acceleration and stops during the trajectory	The child with ADHD performed sequences correctly with a non-linear locomotor pathway. Less functional egocentric strategy. The head and trunk do not move in the same direction.
Spatial memory (location reward) task	[51]	3.7	44	TD	__	__	The ability to form a basic allocentric representation of the environment is present at two years of age. Children's ability to distinguish and remember closely related spatial locations improves from two to 3.5 years of age.
	[28]	4.97 5.3	16 20	TD DS*	__	__	DS participants had more difficulties using allocentric references and learning and remembering locations
KLM	[52]	12	144	TD	They divided the sample into two groups: one with active walking exploration and the other with passive observation.		The active locomotion group needed fewer attempts to learn spatial design. Learning a spatial layout was possible with and without locomotion in children.
	[7]	7.5	96	TD	__	Speed of navigation	Speed navigation is significantly lower in four-year-old children than in ten-year-olds. Learning about relationships between different locations is better from seven years of age. At ten years old they fully develop the ability to learn and orient themselves in the entire space.
	[8]	7.5	30	TD	__	__	Five-year-old children have well-developed egocentric response strategies.
RAM or version of RAM	[31]	6.05 6.06	15 12	TD WS, PWS*	__	Latency and rotation percentages as a chaining strategy	The latency to enter the arms is similar in all groups. PWS and WS participants had turns of less than 45° and more errors, visiting incorrect arms.
	[53]	6.1 6.2	14 14	TD WS*	__	Rotation percentages	Similar results to Foti et al.
	[6]	3.4	10	TD	__	__	Four-year-olds showed accuracy, while two-year-olds performed by chance.

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Table 1 (*continued*)

Test or task	Studies	Mean age (in years)	Sample size	Type of participants	Aspects related to locomotion	Locomotion as a measurement variable	Summary of results
							Children have a spatial memory that will mature between the ages of two and three.
	[54]	4.4	75	TD	They divided children into four groups: WW, WBD, BW and BBD. They analysed the influence of the type of locomotion and active choice	Rotational angles	Children who were trained walking performed better. Children trained in a buggy and without the possibility of active choice made more errors. Both performed better than those who were passively transported or who passively walked. The active choice was the most significant factor in a good performance of the task.
	[55]	5.9	28	TD	Same as Foreman et al., 1990	__	Children without active choice made a high number of errors in the task.
Ofmr task	[56]	5.7	56	TD	__	Distance	During the error trial procedure, the distance travelled was higher. Through observational training, children can transform egocentric information into allocentric more effectively.
Spatial memory (location reward) task	[57]	1.8	72	TD	Condition eliminating self-motion information	__	Performance above chance in the task of disorientation of the viewer's movement. Multisensory information was relevant to their spatial orientation.
Morris Water Maze (adapted)	[34]	1	72	TD	Comparison between crawling and walking children	Latency as hesitation measure/duration of the test	Children crawling for fewer than seven weeks or walking for fewer than eight weeks had fewer successful trials. Older children and those who had more experience in locomotion spent significantly less time hesitating. Spatial training emerged when infants started crawling but improved when children started walking.
Visuo-spatial orientation tests							
Environmental geometry or landmark orientation tests							
	[58]	3.97 16.01	16 16	TD WS*	__	__	The use of geometry and characteristics are derived from different underlying mechanisms. Development trajectories and performance are altered in WS. The combination of information from the two systems is atypical.
	[12]	4.8	160	TD	__	__	Until five years of age, surfaces need to provide visual barriers for spatial representation. Children of all age groups were successful with opaque panels.
	[13]	3.3	96	TD	__	__	The alteration of the shape of the surrounding environment – the extended 3D surface layout – is a crucial factor for children to use a potential landmark to reorient themselves.

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Table 1 (*continued*)

Test or task	Studies	Mean age (in years)	Sample size	Type of participants	Aspects related to locomotion	Locomotion as a measurement variable	Summary of results
	[59]	5.6	49	TD	Viewpoint changed by turning and blindfolding participants	__	6–8-year-olds reoriented themselves regardless of the point of view. 4–5-year-olds depended on the point of view or updating with the movement.
	[60]	3.88	19	TD	__	Trajectory and time	3–5-year-olds easily learned to find the centre of a closed environment using only the geometry of the environment as spatial information.
Immersive reality task	[61]	4	21	TD	Teleporting children to change their viewpoint	__	Children over four years old without physical self-motion information performed better than younger ones.
	[62]	6.1	20	TD	Similar to Negen et al., 2016	__	No use of information about all landmarks together to recall locations during an allocentric reorientation task. Use of the nearest single landmark to reorient (ignoring others).
Y-maze	[63]	10	29	TD	__	Distance, time between starting the trial and the initiation of locomotion and the time and speed during navigation	Variables improve with geometric information rather than landmarks.
Egocentric and allocentric tests	[64] [11]	6 6	62 55	TD TD	__ __	__ __	Similar effectiveness in egocentric and allocentric tasks. Differences between egocentric parts A and B, with higher scores in the first part for all age groups. Until the age of seven, spatial reference frames are not fully developed. 5–7-year-olds used both egocentric and allocentric frames of reference to navigate.
	[65]	6	59 88	TD PT	__	__	PT infants had lower performance in allocentric tasks, related to their visuospatial abilities in reaching space.
Self-reference orientation tests							
	[29]	6.45	28	TD	Comparison of visual vs self-movement information.	__	Better response alternating strategies from trial to trial (landmarks, visual information and self-movement information).
	[66]	10.3	15	TD	Multisensory information on locomotion	Length of turns	10–11-year-olds near-optimally integrate visual and self-motion cues when walking the path, with reduced variability in darkness.
Triangle completion task	[67]	6.5	38	TD	Multisensory information on locomotion	Trajectory, heading and landing errors	From 5 to 7 years of age, landing and heading errors improved per chronological year, with better path integration abilities.
	[68]	8.5	33	TD	Similar to Smith et al., 2013	Measured the path, heading and landing errors	A higher number of yaw rotations produced greater disorientation. The ability to adjust a path could appear at 10–11 years of age.

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Table 1 (*continued*)

Test or task	Studies	Mean age (in years)	Sample size	Type of participants	Aspects related to locomotion	Locomotion as a measurement variable	Summary of results
VHLM	[69]	12.5	10	TD	__	Trajectory, head direction, velocity and latencies.	Locomotor trajectory had a latency to be performed. When learned, children repeat the same trajectory as an automation process. Motor inhibition, mental flexibility and control of impulse responses were exhibited.
Auditory spatial memory test							
Karotz Rabbits test	[70]	9.5	32	TD	__	__	Children at these ages did not demonstrate this competence.
	[71]	1.3	46	TD	__	Rotational angles	18-month-olds used a self-reference system, modulating searches in conjunction with directions and distances. Information from their movement.

TD: Typical development; Y: Years; ASRM: Augmented Reality Spatial Memory; WAlCT: Walking Corsi Test; AWalCT: Adapted Walking Corsi Test; TWalCT: Treasure Walking Corsi Test; OFmr: Open Field with multiple rewards; WS: Williams Syndrome; PWS: Prader Willi Syndrome; GMFCS: Gross motor function classification; PT: Preterm; CP: Cerebral Palsy; SB: Spina Bifida; ORTO/PERI: Orthopaedic devices or peripheral symptoms; WalkOUT: Children who commonly walk both indoors and outdoors; WalkIN: Children who frequently walk indoors and use a wheelchair outdoors; WalkNO: Children who use a wheelchair for all mobility and transfers; MMC: Myelomeningocele; AMC: Arthrogryposis Multiplex Congenita; TSTM: Topographical short-term memory; TL: Topographical learning task; WW: Walked during training and walked during testing; WBD: Walked during training but received directions in a buggy during testing; BW: Trained in a buggy without an active choice but tested on foot; BBD: Trained in a buggy without active choice but tested in a buggy with active choice; VHLM: Virtual House Locomotor Maze; RAM: Radial Arm Maze; *Adult group measured by mental age.

were cross-sectional and observational.

Studies were excluded if: a) Children had conditions other than NDD; b) The main aim was academic performance, language, mathematical or musical outcomes related to visuospatial abilities; c) They were focused on measurements of hormones or nutrition conditions or performed in special environments or considering different socioeconomic situations; d) They were conducted on animal models; and e) Full papers were not written in English.

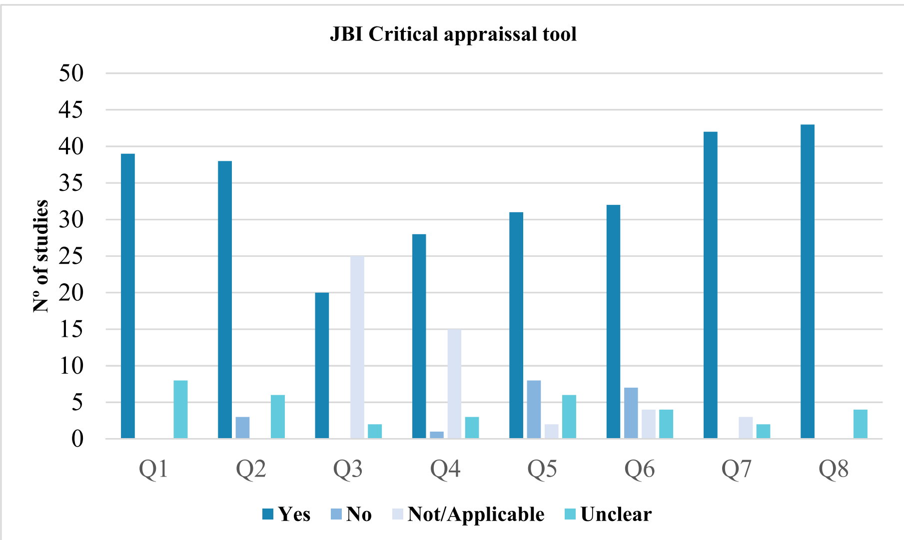

Fig. 2. Quality of articles included in the systematic review measured by Joanna Briggs Institute (JBI) appraisal tool. Most included studies have from moderate to low risk of bias, meeting most of the criteria. Only 9 studies showed a high risk of bias and study limitations were related to the confounding factors (Munn et al., 2015).

2.3. Information sources and search strategies

Relevant articles were identified by searching in MEDLINE (Pubmed), Cochrane Central Register of Controlled Trials (CENTRAL), Web of Science Core Collection and Scielo (WOS), Scopus and PEDro databases and by manual search. The search strategy is described in detail in A1. Supplementary material.

2.4. Data collection and quality assessment

The selection of studies was a three-stage process. Identified citations were independently selected by two reviewers. The first stage was to evaluate the titles found. Articles were included in this first screening if the title mentioned "topographical memory", "navigational memory", "visuospatial memory", "spatial navigation" or "spatial orientation". We then reviewed abstracts to see if they met the criteria. Finally, the full-text articles selected were retrieved and read independently by both reviewers and assessed for inclusion. Any disagreement was resolved by consensus between the two reviewers or a third reviewer when consensus between the first two reviewers could not be reached.

Two reviewers independently extracted data using a specifically designed standardised data extraction form including information related to the study population (age, sex, NDD, etc.), characteristics of the measurement (aim, type, protocol, standardisation, outcomes, etc.) and, specifically, the role of functional locomotion an active exploration variables in the tests analysed. Afterwards, the reviewers compared the extracted data for consistency. All inconsistencies between the two forms were resolved by discussion between the two data extractors. Any disagreement between the data extractors after the initial discussion related to inconsistencies between the two individual data extractions was to be solved by involving a third person. A narrative synthesis of the findings from the included studies was structured around that information.

Two authors determined the methodological quality of the selected studies according to the checklist for analytical cross-sectional studies of the Joanna Briggs Institute of the University of Adelaide (Australia) [38,39] and disagreements were resolved by discussion.

3. Results

The study selection flowchart is presented in Fig. 1. The search strategy identified 3,385 articles. After screening, 47 were included. Assessment descriptions and characteristics are summarised in Table 1. The quality of the studies is shown in Fig. 2 and explained in depth in A2. Supplementary material.

3.1. The role of locomotion in spatial navigation

All studies included walking locomotion to test spatial abilities in extra-personal space but not all of them considered it in the analysis. The articles that considered it did so in two ways: as the outcome variable to be measured or as an explanatory variable.

3.1.1. The study of locomotion as the main outcome measure in spatial navigation

Five studies specifically assessed whether the way locomotion is performed influences spatial memory or spatial orientation in TD and NDD children. Clearfield et al. found that TD infants with less experience in moving (fewer than 7 weeks crawling or 8 weeks walking) had fewer successful trials [34]. Active locomotion allows TD children to learn spatial design [52] whereby active exploration is more important than the type of locomotion [55,54]. The two studies that focused on children with NDD also confirmed that active exploration is more important for spatial navigation than the use of aids to locomote [45,72]. Three papers studied the influence of locomotion in spatial navigation, teleporting children to another virtual environment [62,66], using a chair [59] or moving the space while the children were seated [57].

Self-motion information during locomotion (path integration) was only evaluated in four studies involving TD children. The results are contradictory, with preferences for alternating self-motion and visual inputs [29] or integrating both to execute the task more effectively [66]. Children's landing and heading errors improved every chronological year from five to seven years of age [67], resulting in the ability to adjust a path at ten to eleven years of age and improving throughout their development [68].

3.1.2. The use of locomotion as an explanatory variable

Seven studies used locomotion as an explanatory variable. They measured angles [54,71], percentages [31,53], the sum of rotations in a path reproduction [10,50] or the length of turns [66]. Four studies assessed the trajectory of children when finding a specific location [67,50,60,69] and three considered the influence of distance travelled along a path or with updated angles (mental rotation) [10,56,63]. Variables related to the duration of the task, speed of locomotion, acceleration, number of stops during the tasks, and latency were evaluated by six studies [10,31,34,50,69,63]. Some authors include these perceptive-motor variables to assess navigation efficiency, and some categorise different error patterns.

3.2. Assessments used in spatial navigation

Three types of assessments were classified according to the spatial navigation strategy: visual spatial orientation, visual-spatial memory and auditory spatial orientation. Tests and tasks are described in detail in A3. Supplementary material.

Of the 47 studies, 34 focused on the assessment of spatial navigation components in typically developed (TD) children (from one to

268 participants) and 13 in children with or at risk of NDD (from 12 to 89 participants). Similar percentages of females and males were included.

3.3. Spatial navigation in typically developing children

The mean chronological age of the TD group was 6.4 years (SD = 3.6). The four studies on infants found that spatial training emerges when infants start crawling but improves when they start walking. At 18 months, infants develop a self-reference system to compute the directions and distances of their movements and at two years old they have simple topographical memory strategies [26,34,57,71]. The six studies that included preschool participants found that spatial memory matures between two and three years of age. At three years old, they can orient themselves using landmarks and the geometry of a large environment. The observation of a third person exploring space improves performance [6,13,54,60,56,61].

Most studies focused on children from four years of age, four of them on children from six to twelve years old [10,66,63,70] and most of the studies included in this review considered participants from preschool to twelve years old. From five years onwards, spatial memory starts to improve. From six years of age, they reorient themselves to find a hidden object in a geometric feature inside a room after being blindfolded and moved to change their perspective of the feature. From five to seven years old, they use egocentric and allocentric frames of reference. At seven years old, learning about relationships between different locations improves and they are more accurate at calculating heading and distance in space. At around ten years of age, they fully develop the ability to learn and orient themselves in the entire space, navigating more effectively and using geometric rather than landmark references. From about then until the age of eleven, children reproduce a path integrating visual and self-motion cues.

3.4. Spatial navigation in children with neurodevelopmental disabilities

In the studies on children with or at risk of NDD, the mean age was 5.6 years (SD = 3.5). Twelve of the 47 studies assessed spatial abilities in individuals with physical or intellectual NDD. Four of them focused on CP children, using the MC and the WalCT [16–18,48]. Spatial memory outcomes of children with CP changed depending on the study and tool used (MC or WalCT). Related to gross motor function, clinical severity appeared to play an important role in spatial functions in both reaching and locomotor spaces. Three studies used the WalCT in children with spina bifida, myelomeningocele, CP, and arthrogryposis multiplex congenita and with orthopaedic or peripheral symptoms [17,45,46]. The type of everyday mobility affects children's spatial navigation. Children who had independent walking ability and walked outside every day had better short-term spatial memory than those who only walked indoors and those who always used a wheelchair to move around.

Other studies compared the execution of spatial memory in populations with intellectual NDD and a control group, with only two studies that assessed spatial orientation. They included WS [53,58] Prader-Willi syndrome (PWS) [31] and DS participants [28,33] and used the floor matrix task for those with DS [33] and the RAM for those with WS and PWS [53]. Participants with PWS, WS, and DS showed lower spatial memory scores and had difficulties in explorative capacity, task initiation, cognitive planning, and use of allocentric reference frames. Another two studies evaluated spatial abilities in children with ADHD using the WalCT and the VCTH [50,47]. Children with ADHD have lower performance in terms of topographical memory and more perseverative errors, reflecting more cognitive inflexibility. However, reproducing a path after 5 min – which depends more on long-term memory – was unaffected. The preterm population shows lower performance in topographical memory, which is further affected by their level of attention [26] and spatial orientation [65].

4. Discussion

The present systematic review aimed to provide information about the role of locomotion in the assessment of spatial navigation in children and describe the tests and tools used to evaluate it and the spatial outcomes in children with NDD and TD children. To this end, 47 articles were analysed. Methodologically, although most studies included in this review are of a high quality, the variability of sample size, the use of mental age rather than chronological age, and the lack of inclusion of confounding factors in the analysis must be considered. The variety of terms to refer to spatial navigation hindered the selection and interpretation of the studies.

4.1. Locomotor strategies assessed during spatial navigation

At 18 months, infants use self-reference information to compute their directions and distances during locomotion, which is essential to their first perceptive-motor experiences [34,71,73]. By using vestibular and proprioceptive information about self-motion, children calculate the direction of movement and update their body's location in relation to objects and moving bodies [20,67,74–78]. Perceptive-motor information has been traditionally studied through the child's capacity to use a body-based frame of reference. Along these lines, path integration characteristics throughout infant growth have not been fully studied, and a lack of tools has been identified in this field [67,79,80]. In this review, only four articles specifically focused on the assessment of path integration in TD children [29,66,67,68]. The standardised test designed to assess it in TD children is the triangle completion task [67,68], in which visual information is eliminated by blindfolding the children. The vestibular and proprioceptive information is assessed by analysing landing and heading errors, and performance improves every chronological year from five to seven years of age. Children's preference for visual or proprioceptive and vestibular information when reproducing a path is not yet clear [29,66].

Surprisingly, no paper focused on evaluating path integration in children with NDD. This is an important point because studies in children with CP showed that spatial navigation is affected by perceptual-motor impairments, which hinder plan organisation and movement guidance [21,81]. It could be the reason why differences in navigation speed, gait stabilisation, head and gaze anticipation, trajectory formation, and head and trunk movements have also been found in this population, using other tests such as the WalCT and the MC [15,16,18].

Interestingly, locomotor performance has been considered separately in other articles, both in TD children and children with NDD, by measuring rotations [10,31,54,66,50,53,71], trajectory [67,50,60,69], distance [10,56,63] and variables related to time [10,31,34,50,69,63].

Taking all of the information into consideration, standardised instruments would need to include procedures to assess perceptive-motor strategies targeted at children with NDD. Also, it would be essential to develop them considering early childhood, helping to detect difficulties as soon as possible, and especially prioritising the needs to be supported. Importantly, the assessment and therapies aimed at encouraging spatial memory and spatial orientation abilities in children must also consider the influence of locomotion variables in spatial navigation.

4.2. Motor and cognitive impairments impact spatial navigation in children with NDD

Considering spatial navigation as a multidimensional function, both perceptive-motor and cognitive information interact. Studies in children with intellectual NDD such as DS, WS, or PWS showed lower exploratory capacity, initiation, or cognitive planning [31,33,53,58]. In agreement with these results, some other authors have found that children with these syndromes [27–29] together with children with a heterogeneous group of disorders such as autism spectrum disorder or ADHD, perform worse in terms of spatial abilities [47,82–86]. In children with ADHD-C, the short-term memory, which is needed to learn a new path, is more affected than the long-term memory [87]. Importantly, short-term-memory deficits have been related to difficulties with sustained attention and motor inhibition [50,47]. Similarly, differences in spatial orientation [65] and spatial memory have been found in preterm populations, which are also influenced by attention. In fact, better outcomes were achieved when young children were asked to perform a more motivational task [26]. Although these studies described spatial memory outcomes in children with or at risk of NDD, they did not include specific motor measurements during navigational tasks and were not very informative about the relative influence of movement on spatial outcomes [31,33,53,58,65,87]. Nevertheless, both are routine aspects for therapists, who must consider not only motor parameters during locomotion but also the influence of cognitive strategies such as attention, cognitive flexibility, or motor inhibitory control in children with NDD, including motivational tasks or observational training in their locomotion assessments and interventions.

The relationship between motor function and spatial navigation confirms the need to explore how motor outcomes affect the development of spatial navigation, even in a population with intellectual NDD. Children with limited postural control and limited exploration not only have worse spatial performance but are also at risk of global developmental impairments [73]. Obviously, the influence of motor function in spatial navigation is studied more indepth in children whose motor function is the most affected. In the CP population, the level of gross motor function has been related to worse spatial navigation, specifically in children with Gross Motor Function Levels II and III [18,48,46]. These results are in line with others that describe a worse performance of spatial abilities in children with motor NDD [14,21,81]. Unfortunately, studies on the NDD population are scarce and mainly focused on children from five years of age [17,18,31,33,45,53,46,48,58].

4.3. During functional locomotion, active exploration is more important than motor function

Even though the cognitive and perceptive-motor influence on spatial performance in children with NDD is clear, this review points out that having the possibility to actively explore the environment influences spatial navigation. This result is independent of whether the child uses orthopaedic devices to move around, such as wheelchairs and walkers, or is passively propelled [17]. Studies highlight the importance of enhancing and facilitating active exploration in children with NDD as early as possible, regardless of their mode of locomotion. Interestingly, comparable results have been found in TD children who were passively transported and could make active choices to move. They showed similar spatial learning to those who use locomotion but, on the contrary, do not have an active choice in their movements to explore the space around them [55,54].

Future studies should specifically analyse how locomotor variables influence the development of spatial navigation in children and be more focused on children with NDD. They should include locomotor variables in the spatial navigation assessment and starting to evaluate it as soon as children start to locomote.

5. Conclusions

Moving improves spatial navigation, but more important than how we locomote is having the choice of actively exploring the environment. Children with or at risk of NDD perform worse regarding spatial navigation. It is necessary to have tools to assess, describe, and identify this ability in this population as soon as possible. More research is needed to establish standardized procedures for assessing spatial navigation in children with or at risk of NDD, considering locomotion variables and cognitive functions such as attention or control of inhibition and how they also impact spatial navigation and exploratory capacities.

Ethical approval

Ethical approval and consent of patients to participate are not applicable to our study.

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Data availability

Data are available on Zenodo at https://doi.org/10.5281/zenodo.10621560.

CRediT authorship contribution statement

Nuria Martín-Pozuelo: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lidia Carballo-Costa:** Writing – review & editing, Visualization, Validation, Methodology. **Marina Solís-García:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Marco Giancola:** Writing – review & editing, Visualization, Formal analysis. **Laura Piccardi:** Writing – review & editing, Writing – original draft, Supervision, Resources, Investigation, Funding acquisition, Conceptualization. **Isabel De las Cuevas-Terán:** Writing – review & editing, Visualization, Resources, Project administration, Investigation, Formal analysis, Data curation, Conceptualization. **Verónica Robles-García:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Investigation, Funding acquisition, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that no AI or AI-assisted technology was used in the writing process.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.heliyon.2024.e33817.

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