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Embodied Interaction and Spatial Skills: A Systematic Review of Empirical Studies

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Embodied interaction describes the interplay between the brain and the body and its influence on the sharing, creation and manipulation of meaningful interactions with technology. Spatial skills entail the acquisition, organization, utilization and revision of knowledge about spatial environments. Embodied interaction is a rapidly growing topic in human–computer interaction with the potential to amplify human interaction and communication capacities, while spatial skills are regarded as key enablers for the successful management of cognitive tasks. This work provides a systematic review of empirical studies focused on embodied interaction and spatial skills. Thirty-six peer-reviewed articles were systematically collected and analysed according to their main elements. The results summarize and distil the developments concerning embodied interaction and spatial skills over the past decade. We identify embodied interaction capacities found in the literature review that help us to enhance and develop spatial skills. Lastly, we discuss implications for research and practice and highlight directions for future work.

RESEARCH HIGHLIGHTS

- Systematically reviewed 36 studies to identify aspects of embodied interaction and spatial skills convergence that have been the focus of publications between 2008 and 2018.
- Assessed embodied interaction-based spatial skills interventions, paying specific attention to the employed technologies, targeted spatial skills and main thematic categorizations of the research questions.
- Discuss three capacities of embodied interaction that might catalyse the development and enhancement of spatial skills engagement: namely, enrichment, transferability and convergent smart physicality.

Keywords: interaction techniques; embodied interaction; spatial reasoning; spatial skills; spatial abilities; systematic literature review

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1. INTRODUCTION

Spatial skills (SS) refer to a collection of cognitive functions and aptitudes that are considered a critical component of human intelligence (Gardner, 2011). They can be defined as a human's capacity to understand, reason over, recall and manipulate the spatial relations among objects or in space. Several studies have noted that advanced understanding of SS is essential for success in various domains, such as chemistry (Wu & Shah, 2004), engineering (Potter & Van der Merwe, 2003), medical surgery (Eyal & Tendick, 2001), computer-aided design software (Hamlin *et al.*, 2006) and science, technology, engineering and mathematics (STEM) (Buckley *et al.*, 2018, Sorby, 2009, Wai *et al.*, 2009). In daily life, SS are essential to activities like driving and orienting vehicles in unfamiliar physical surroundings (Lajoie, 2003). In addition, they are used in more leisurely activities, such as folding paper during origami and solving a Rubik's cube or puzzle. Their wide range of applications has led researchers to categorize SS as either small scale (i.e. figural) or large scale (i.e. environmental) (Hegarty & Waller, 2005). Small-scale spatial abilities include perception of horizontality, mental rotation of objects and location of simple figures within complex figures (e.g. (Linn & Petersen, 1985, Voyer *et al.*, 1995)). In contrast to small-scale SS, much less attention has been given to larger scale, also referred to as *environmental*, SS (Hegarty *et al.*, 2006). Large-scale SS include learning the layout of new spaces (e.g. buildings or cities), navigation in known spaces and giving/interpreting navigation instructions (Hegarty *et al.*, 2006). Large-scale SS relate more directly to physical body movement and context (i.e. they are relevant for embodied interaction) and are connected with activities that occur in more extensive real or virtual spaces. The literature indicates that SS of different spatial scales are partially (but not completely) dissociated (Hegarty *et al.*, 2006, Hegarty & Waller, 2005), and thus it is reasonable to study them separately.

Moreover, SS are heavily connected with the learning sciences, since they are related to the meta-cognitive learning of science and engineering (Wai *et al.*, 2009, Wang *et al.*, 2007). In addition to influencing the capacity to understand and perform scientific work, SS may affect perceptions at the meta-cognitive and affective levels. Consequently, there is great merit in research that develops technologies to enhance SS and equip citizens with affordances and competences for the future (Clifton *et al.*, 2016, Wai *et al.*, 2009).

Contemporary technological advancements (e.g. television, film and video games) augment basic visuo-spatial skills, such as spatial orientation (Gagnon, 1985), spatial visualization (Greenfield *et al.*, 1994) and other visual abilities (Subrahmanyam & Greenfield, 1994) deemed necessary and important when interacting with machines (Scarr *et al.*, 2013). Dourish (2004) furthers interaction design, with the term embodied interaction (EI), which offers a new model of interpreting interaction that extends recent human–computer interaction (HCI) research trends in 'tangible' and 'social' computing and is defined as indicating that 'how we understand the world, ourselves and interaction comes from our location in a physical and social world of embodied factors'. The past decade has witnessed a rise in exploration of SS through technologies that leverage EI (Clifton *et al.*, 2016). In an attempt to understand the collective ramifications of these works, researchers in cognitive science and HCI have begun closely exploring the interplay between movement, cognition and SS (Clifton *et al.*, 2016). Understanding these relationships may yield significant positive implications, such as guiding researchers and HCI designers in the creation of future blueprints, principles and interventions capable of developing and enhancing SS.

A growing body of literature occupies the intersection of EI and SS; however, there is limited work on established general knowledge in addition to the development of more sophisticated abstract concepts. The lack of systematic review in this space significantly hinders research concerning the highly promising value of EI to support SS, leaving practitioners and researchers in uncharted territory when faced with implementing EI designs to develop or enhance SS (e.g. grabbing objects, moving objects, etc.). In order to derive meaningful theoretical and practical implications, as well as identify important areas of future research, it is critical to understand how the core artefacts pertinent to EI are able to amplify SS. In this paper we present a systematic literature review (SLR) (Kitchenham & Charters, 2007) on the intersection of EI and SS that uncovers initial findings on the value of EI to support SS, while also delineating several promising research streams.

The remainder of the paper is structured as follows. First, we describe the guiding research question (RQ) that drive this review. Then, in section 3, we discuss the relevant theoretical grounds and related work. In section 4, we detail the research methodology used to conduct the SLR and lay out the main steps followed. In section 5, we outline the research findings derived from the data analysis based on the specific areas of focus. In section 6, we discuss the findings, the implications for research and practice and the limitations of the selected approach. Finally, in section 7, we finish with concluding remarks.

2. REVIEW QUESTIONS

Our review is driven by an overarching RQ, which is further divided into four sub-RQs. Defining concise sub-questions facilitates us in addressing our overarching RQ, by partitioning the entirety of our research, such that different aspects may be discussed clearly and directly.

Technological advancements have led to an upturn in works, which leverage EI-based capacities to support SS. These studies take into account embodied skills, while focusing on expressive movements and 'rich' interactions with 'strong specific' products tailored to targeted domains (Hornecker & Buur, 2006, Marshall *et al.*, 2013). Our literature review aims to tease apart these concerns and investigates how these elements have been utilized over the past decade in EI-based SS research. Therefore, in this review, we aim to identify:

RQ: What are the research advancements in the intersection of embodied interaction and spatial skills?

Specifically, we first identify the contextual and methodological details of the identified interventions focusing on EI and SS. This will allow us to identify trends, established methods in the field and potential gaps that may inform future work. The first sub-RQ of this review asks:

RQ1: What user groups and employed methodologies have been the focus of contemporary research in embodied interaction and spatial skills?

The second sub-RQ explores the underlying technologies employed and the capacities of EI that are leveraged across the various technological solutions and physical set-ups. Therefore, the second sub-RQ is:

RQ2: How has embodied interaction been realized through the selection of technology, physical action, mapping and scale?

The third sub-RQ examines the distribution and assessment of SS and how these are implemented in the context of the various interventions and the role of EI. Hence, the third sub-RQ focuses on:

RQ3: How were the spatial skills distributed and assessed, and what was their purpose?

Lastly, the final sub-RQ focuses on identifying the capacities of EI that were utilized throughout various interventions to support SS, and the respective outcomes of these interventions. Therefore, the final sub-RQ inquires:

RQ4: How has embodied interaction been leveraged to develop or enhance spatial skills and what are the implications for research and practice?

3. RELATED WORK

3.1. Spatial Skills

Researchers have engaged in contentious discourse in attempts to establish an explicit definition of spatial ability (Hegarty & Waller, 2005, Linn & Petersen, 1985, Sorby, 2009, Uttal *et al.*, 2013). Hegarty & Waller (2005) differentiate spatial ability from general intelligence in a historical overview examining the corpus of factor-analytic literature centred on identifying natural individual differences in spatial abilities. Their work provides evidence that reinforces the presumed hypothesis that regards spatial ability as a collection of different competencies, as opposed to a solitary skill (Hegarty & Waller, 2005, Sorby, 2009). However, discussion surrounding the skills entailed has also caused longstanding disagreement, with multiple researchers proposing overlapping hierarchical structures of spatial abilities. For example, Linn & Petersen (1985) subscribe to a breakdown of spatial ability into the following three sub-skills: spatial visualization, spatial perception and mental rotation. Lohman (1988) proposed spatial visualization, spatial relations and spatial orientation. Alternatively, Maier combines the aforementioned categories to produce a set of five spatial sub-skills: spatial visualization, spatial perception, mental rotation, spatial relations and spatial orientation (Sorby, 2009). This is by no means an exhaustive account of the conflicting definitions put forward but serves to illustrate the controversial discourse regarding spatial ability and its constituent factors. Based on this state of disunity, Hegarty & Waller (2005) highlight the need for a theoretical framework to better assess the current state of spatial abilities research by providing a common foundation for skills comprehension and assessment.

Researchers have also proposed several classification systems in attempts to taxonomize spatial sub-skills (Buckley *et al.*, 2018, Sorby, 2009, Uttal *et al.*, 2013). Tartre (1990) advocated a hierarchy based on the different cognitive functions involved when engaged in specific spatial tasks. He offered two main categories, spatial orientation and spatial visualization, the latter of which was further divided into mental rotations and mental transformations. This implicitly defined four non-mutually exclusive sub-categories of spatial ability. Alternatively, Uttal *et al.* (2013) positioned SS inside a two-dimensional matrix by evaluating their tendencies across two core dimensions: the intrinsic versus extrinsic, and static versus dynamic assessment of the spatial information involved. The former distinction (intrinsic versus extrinsic) determines whether the spatial relations of interest are purely self referential. The intrinsic case applies when the focus centres on how an object relates to itself, whereas the extrinsic case applies when the concern lies in how an the objects connects externally to surrounding objects or to elements in its environment. The latter distinction characterizes spatial information as static when lacking movement, and dynamic otherwise. Uttal *et al.* (2013) argue that by assessing spatial information according to its selected dimensions, their topology is able to differentiate between SS using a more granular approach than pre-existing classification systems, and thus, provides a more accurate representation of SS. Moreover, they demonstrate topological efficacy and inclusion by mapping existing classifications onto their matrix.

In a completely different approach, Buckley *et al.* (2018) suggest a SS framework built on the foundation of the Cattell–Horn–Carroll (CHC) theory (Sternberg & Kaufman, 2011) of cognitive factors. CHC theory refers to SS as visual processing and recognizes this as one of 16 primary mental abilities that establish general intelligence (it should be noted that classifying SS as a sub-component of general intelligence contradicts Hagerty's evidence (Hegarty & Waller, 2005) that separates spatial from general intelligence, as mentioned above). The authors further granularize many of the original 11 spatial factors according to the movement dimension (static versus dynamic) proposed by Uttal *et al.* (2013), and recognize and implement the need to supplement the results with additional spatial factors. The derived cumulative theoretical framework organizes 25 cognitive factors of spatial ability into static and dynamic groupings. In addition, Buckley *et al.* (2018) highlight the relationships between different spatial factors within their proposed framework. Lastly, they emphasize their contribution's predisposition for malleability as an implicit benefit of basing their framework on CHC theory, as it enables the adoption of newly discovered spatial factors, and the removal or coalescence of pre-existing factors, and can thus withstand the progression of research that defines the continued evolution of spatial ability.

Despite the diversity of frameworks and taxonomies to conceptualize and categorize different SS, related work converges on the idea that SS can be defined as a human's capacity to understand, reason over, recall and manipulate the spatial relations among objects or in space. Furthermore, four common themes are acknowledged: namely, spatial perception, spatial visualization, mental folding and mental rotation. Each of these areas has extreme importance when interacting with a machine (Scarr *et al.*, 2013), especially when such interaction is expressed through our physical body (i.e. EI) (Clifton *et al.*, 2016).

3.2. Embodied Cognition and Interaction

Embodied cognition emphasizes the importance of the relationship between the mind and the body, and its interactions with the surrounding environment, in the acquisition, development and understanding of knowledge (Wilson, 2002). It counters ideologies of disembodied rationality by placing our physicality, associated sensorimotor system and contextual engagement as a focal point of cognitive development. In her highly esteemed work *Six Views of Embodied Cognition*, Wilson (2002) challenged the most prominent claims central to the construction of embodied cognition theory and discussed in-depth the situated nature of task-based learning, the influence of real-time pressures on cognitive development, and humans' ability to offload cognitive work onto their surrounding environment and perceptual and motor control system. Additionally, Wilson (2002) posits that 'off-line cognition is body based' and, in particular, that reasoning and problem solving benefit greatly from the creation of spatial mental models.

The application of embodied cognition theory to human interactions with technological systems and artefacts gives rise to EI: a perspective on the relationship between people and systems that has been enabled by recent technological advances in wearables, handhelds and tabletops, high precision motion tracking systems and virtual reality (VR). Dourish (2004) characterizes EI by how the coupling of mental faculties and physical action, combined with the social and environmental context, influences the creation, manipulation and sharing of natural and meaningful interactions with technology (i.e. via gesture or facial expression). Thus, these embodied technologies participate in the world they represent, turning action into meaning (Dourish, 2004), and demonstrating the capacity to play an instrumental role in the creation of meaningful interactive user experiences.

Within the EI paradigm, researchers have explored the application of several complementary theoretical models and offered a plethora of guidelines and design frameworks aimed at facilitating the integration of physicality and computational practices (Antle *et al.*, 2009b, Hornecker & Buur, 2006, Hurtienne & Israel, 2007, Klemmer *et al.*, 2006). For example, Hurtienne & Israel (2007) derive a taxonomy for intuitive interaction to classify tangible interactions based on image schemas and their metaphorical extensions. Image schemas (also referred to as embodied schemas (Antle *et al.*, 2009b)) are abstract representations of recurring dynamic patterns, within our cognitive processes, of bodily interactions that structure the way we understand and reason with the world (Lakoff & Johnson, 1980). Image schemas are created from the spatial structure of objects and their movements and are formed and shaped from our bodily interactions (Mandler, 1992). According to Hurtienne & Israel (2007), their ability to represent abstract concepts through metaphorical extension contributes to their role as 'common primitives of thought'. Building on this, Antle *et al.* (2009b) explore the application of embodied metaphor theory (Lakoff & Johnson, 1980) to digitally augmented physical environments. Rooted in sensorimotor experiences, embodied metaphors formalize knowledge by establishing conceptual mappings between a concrete source domain and an abstract target domain. Further, if these embodied metaphors underpin the conceptualization of information, then their understanding could inform the design of embodied interactive experiences (such as designing intuitive tangible interactions).

Synthesizing theories on embodiment emerging from psychology, sociology and philosophy, Klemmer *et al.* (2006) present a collection of five themes with the aim of supporting researchers during the ideation, design and evaluation of EI-based systems. Among these, they advocate the saliency of *thinking through doing* and revisit the cognitive advantages, previously highlighted by Wilson (2002), which result from strategically offloading mental computation onto the surrounding environment through epistemic and pragmatic actions. The seminal works by Kirsh & Maglio (1994) first introduced epistemic actions as 'physical actions that make mental computation easier, faster or more reliable' by performing computational actions (i.e. altering one's own computational state (Kirsh & Maglio, 1994)). By performing such actions, the user reduces their need to preload information that is mentally difficult to compute and, rather, uncovers it on a need-to-know basis (Kirsh & Maglio, 1994, Wilson, 2002). Pragmatic actions, on the other hand, are distinguished as 'actions performed to bring one physically closer to a goal' (Kirsh & Maglio, 1994). Rather than making the problem space more tractable, their primary function is strictly aimed at task accomplishment. In an analysis investigating how different interaction techniques facilitate the development of children's thinking skills while solving spatial puzzles, Antle (2013) examined the affordances of physical, graphical and tangible interfaces through the complementarity of epistemic and pragmatic actions and the *theory of complementary actions*. While Antle (2013) acknowledges that there is no one-size-fits-all solution, she posits that physical interaction can benefit greatly from the integration of tangible affordances. Further, she leverages the theory of complementary actions to provide key concepts and explanatory details regarding how and why using our hands to manipulate objects holds the potential to augment our spatial problem-solving abilities (Kirsh, 1995).

3.3. Embodied Interaction and Spatial Skills

EI naturally bears unique affordances for both STEM education and learning in general. Consequently, EI has inspired a broad range of educational activity designs (Abrahamson & Trninic, 2011, Marshall, 2007). However, thus far systematic work investigating the potential of EI's affordances to support SS is lacking. In this section we draw special attention to a collection of noteworthy studies that have taken initial steps towards understanding SS through the lens of EI.

Baykal *et al.* (2018) explored the complementary relationship between tangible user interfaces (TUI) and SS development in a review of empirical studies centred on early spatial learning in pre-school children (aged 2 to 4). They suggest that the positive impacts of TUI on learning emerge in part from the embodied nature of haptic interactions and movement, combined with the inherent spatial nature of physicality. Moreover, they identify a collection of tangible physical objects (i.e. manipulatives) with spatial properties (e.g. Fröbel gifts and tangrams) and consider how the mental rotation skills of young children might benefit from digitization and adoption of novel interaction mechanisms, such as gestural input, story-telling and guided play. One such advantage is enabling users to participate more actively in the design process of tangible spatial learning interventions by providing a story and a corresponding tool that facilitates communication with such young users. In conclusion, they present a framework that outlines the relationship between design recommendations for the development of SS and use of TUI for learning in pre-school children. Though this paper rests on the embodiment and physicality of tangibles to address the concerns of SS development, and contributes greatly to the domain of intervention design for young learners, due to the limited age range and unsystematic nature of their search we observe that this work does not adequately address our central research questions.

Clifton *et al.* (2016) emphasize the need to provide empirically and theoretically grounded methods for training in SS to address the growing demand for competencies in STEM domains. Their work is positioned on the early contributions of Montello (1993) on the human psychology of spatial understanding, which theorized that spatial scale greatly influences how humans understand and manage their surrounding spatial information. They present a design space to classify the relationships between scale-based embodiment and elements of spatial cognition in tangible, embedded and embodied interaction (TEI) systems. *Scale-based* refers to the mechanisms constructed to establish embodiment. Clifton *et al.* (2016) assign spatial aspects into three categories relating to demonstrated abilities, perception and navigation. Specifically, a system has *environmental* scale if it involves navigation of physical or virtual spaces: for example, traversing a maze constructed with interactive floor tiles that may assist with way-finding (Boari & Fraser, 2009). *Figural* scale is when the EI concerns small movements in space using physical or virtual stimuli. Chiu *et al.* (2018) exemplify this in their gestural interface for manipulating digital objects in a shape construction game. Finally, *vista* scale presents extensive visual information, typically distanced from the user, as a means to promote EI. This concept is exemplified by Berlin's annual Festival of Lights, which celebrates static and dynamic projection-mapping technology. Moreover, Clifton *et al.* (2016) identify and systematize a collection of recent interventions in accordance with their proposed topology to identify important trends in the existing literature. They emphasize the observed relationships between the scale of EI and specific SS as the leading trends. Their analysis exposes the untapped areas that hold potential for future research to take shape and provides increased understanding of the interplay between embodied interfaces and spatial cognition with respect to their design space.

We highlight Clifton *et al.* (2016) as pioneers in the overlap of spatial cognition and embodiment enabled through TEI systems. By devising a design space specifically formulated to assess the relationship between the aforementioned dimensions, they have lain the groundwork for future research. However, it must be acknowledged that this work is neither systematically performed nor does it represent an exhaustive overview of the corpus of research in this space. Thus, considerable room remains for deeper assessment of the literature.

Although EI and SS have several commonalities and their interplay demonstrates great potential, their alignment and convergence in the HCI literature are still limited. To address this issue, the research community must expand in both directions: by considering the main affordances of EI that can be utilized to activate SS, and by determining how SS can embrace EI's capacities. Consequently, the current review investigates the convergence and synergy between EI and SS in order to summarize the current findings, categorize the contemporary advances in the intersection of EI and SS and guide future research.

4. METHODOLOGY

4.1. Overview

To address the aforementioned questions, a team of two researchers conducted a SLR on the intersection of EI and SS. As a means to minimize research bias and enable reproducibility, the authors developed a review protocol by following the Kitchenham & Charters (2007)'s methodology for SLR. The two researchers discussed and resolved any in-explicit aspects of the reviewed papers in consensus meetings.

4.2. Review Planning

To the best of the authors' knowledge, there does not exist an SLR on EI and SS. Thus, the intention of this work is to provide a methodically formulated synopsis of the empirical research that constitutes the state of the art in this field. The authors aim to thoroughly discuss the ramifications of the aggregate results, specifically concerning the targeted SS, technologies utilized to realize embodiment, methodologies employed and, finally, the capacities of EI to enhance SS. Such findings may be beneficial to an assortment of stakeholders (i.e. researchers in HCI, edu-

TABLE 1. An overview of the raw results by source from the primary and secondary search, including data source, additional filters applied, initial number of results returned and final number of remaining articles upon completion of the winnowing process.

Data sources	Filters	# Raw results	# Primary search papers	# Snowball papers	# Total papers
ACM	Content type: PDF	452	22	1	23
IEEE	Content type: conferences, journals and magazines, early access articles	51	1	3	4
Science Direct	Article type: conferences, abstracts, data articles, research articles Language: English	124	3	0	3
Springer	Content type: articles, conference papers Discipline: education, computer science, engineering	961	1	1	2
Taylor & Francis	Only content authors have access to	126	2	1	3
Wiley	Publication type: journals	28	0	0	0
Google Scholar	Language: English	40	0	0	0
Total		1782	29	7	36

cators in technology enhanced learning (TEL), virtual reality (VR)/augmented reality (AR)/mixed reality (MR) exergame developers) by encapsulating a comprehensive overview on how the relationship between EI and SS has been interpreted, exploited and validated in the literature over time.

4.3. Search Strategies

The search for primary sources was restricted to peer-reviewed studies containing empirically sourced data. The systematic review was conducted across the following six academic databases: ACM Digital Library, IEEE Xplore, Springer Link, Science Direct, Taylor & Francis and Wiley. When possible, additional search filters were employed in order to narrow the initial collection of retrieved search results. Table 1 illustrates the databases searched and the corresponding filters applied. As a precautionary measure, Google Scholar was also included to account for the existence of unindexed relevant works. Additionally, and despite the fact that those special issues are part of the already searched academic databases, the authors manually examined the article titles contained in specific journals and special issues with relevant themes (i.e. Transactions on Computer–Human Interactions vol. 15 no. 3, vol. 25 no.1; British Journal of Educational Technology vol. 41 no. 1, vol 49 no. 6; Behaviour & Information Technology vol. 27 no. 1, vol. 37 no. 8). Lastly, references for the selected primary studies were also searched according to the snowball technique presented in Wohlin (2014). The authors scoped the search to include studies as early as 2008. Thus, each database was covered from January 1, 2008, to August 12, 2018. We chose this decade-long window for two reasons. First, the end of the 2000s welcomed the development and commercialization of technologies with the capacity to transition users away from the traditional mouse and keyboard, making devices such as the tablet and interactive tabletop readily accessible to the general population. In addition, advances in sensing technologies (i.e. Microsoft Kinect, Leap Motion, MYO) provided new ways for users to interact and direct technology with their bodies, thereby strengthening the arsenal with which to cultivate EI based studies. Second, the dominant computer science conferences in these areas, ACM Tangible, Embedded and Embodied Interaction (TEI) and ACM Spatial User Interaction (SUI), were not established until 2007 and 2013, respectively. Selecting search terms for an accurate and inclusive review on the intersection of EI and SS proved challenging. Terms that are *too* general result in an unwieldy set of papers, while terms that are *too* specific are likely to miss relevant papers. After some trial and error with a range of databases, discussions between the authors and identification of terms causing false positives and false negatives (i.e. Type 1 and 2 errors), we concluded on the following search string to capture the area of interest: the search term used was *Embodied AND Interaction AND (Spatial reasoning OR Spatial ability OR Spatial skill)*.

4.4. Selection Criteria

To filter the initial primary studies obtained from the database search, the authors agreed to adopt the six inclusion exclusion criteria shown in Table 2. Further analysis was conducted by assessing each paper in relation to the quality criteria outlined in Table 3, in conjunction with the critical evaluation principles discussed in Oates (2005). Specifically, this affirms that research must be sufficiently rigorous and relevant, where rigour signifies that the research was systematically conducted, and that the complete process upholds a high degree of validity.

4.5. Review Execution

The review protocol was conducted in four distinct stages: namely, (i) searching the literature to identify relevant articles, (ii) reviewing and evaluating the articles to limit their scope

TABLE 2. Inclusion exclusion criteria employed during initial stage of winnowing retrieved primary studies.

Include	Exclude
• Focus on spatial reasoning and embodied interaction • Published between 2008 and 2018 • Journal articles and conference proceedings	• Targeted clinical trials • Not published in English • Non-peer-reviewed papers (theoretical essays, tool demonstrations, workshops, work in progress, posters, etc.)

TABLE 3. The quality criteria used during analysis of the primary studies.

Quality Criteria
1. Are the research questions clearly explained and their purpose justified?
2. Is the research strategy explicitly defined?
3. Is the research design suitable/appropriate for addressing the research questions?
4. Is the research methodology transparently reported (participants, instruments, data collection and analysis)?
5. Are the employed data analysis techniques rigorous?
6. Are the findings clearly communicated and their limitations discussed?
7. Are the extrapolated generalized results reasonable?

and quality based on the aforementioned criteria, (iii) coding the results and (iv) reporting the review. In this section, we address the first two stages by detailing the three-step winnowing process used to identify studies relevant to our research questions. The authors queried the six selected online databases with the search term *Embodied AND Interaction AND (Spatial reasoning OR Spatial ability OR Spatial skill)* and corresponding filters between January 1, 2008, and August 12, 2018. The first four pages of Google Scholar were also considered. Our search terms produced a total of 1782 articles across the set of online data sources. Initial results from the online database search, paired with corresponding filters, are shown in Table 1.

Step 1 was designed to quickly remove extraneous studies by reading only their title and keywords. Specifically, a study was excluded if its title signified that its primary focus was outside the intersection of EI and spatial reasoning, abilities or skills. Studies that were conducted on clinical populations were also removed. For example, an article concerning interactive textile interfaces and children with autism spectrum disorder would be excluded. In the event that a title alone did not provide sufficient information to justify exclusion, a study was carried through to the next round. Upon completion of Step 1, 92 studies remained.

During Step 2, the abstracts of the 92 studies were carefully read to ensure that each presented empirical data obtained by adhering to appropriate and rigorous research designs, as identified by Ross & Morrison (1996) and Oates (2005). If such information could not be determined from abstract alone, the reviewers examined the article contents. This iteration also eliminated poster papers, work-in-progress papers, extended abstracts, tool demonstrations, theoretical papers and book chapters. The authors referred to the inclusion exclusion criteria outlined in Table 2 during both Steps 1 and 2. In total, there were 38 papers after the completion of Step 2.

Step 3 consisted of a thorough read of the 38 remaining articles to provide the foundation for analysis of these works. The authors carefully considered each paper according to the predetermined quality criteria shown in Table 3. Multiple publications on the same data were reduced to include only a single study. For example, if a study appeared as both a short and a long paper, the most relevant version was included and the other(s) discarded. In addition, we aimed to identify papers that focused on SS beyond the inherent spatial nature of EI. Thus, we kept only studies with actions purposefully designed to create, share or manipulate SS, knowledge or experiences through interactions with a technological system. Step 3 yielded 29 relevant articles.

Additionally, the researchers carefully examined all article titles belonging to relevant special issues of the following three journals: *British Journal of Educational Technology, Behaviour & Information Technology and Transactions on Computer–Human Interaction*. Performing this additional measure did not return any new papers to consider. Lastly, the 'Snowballing' secondary search technique (Wohlin, 2014) was applied to the citations included in the references section of the aforementioned 29 key studies. A total of 390 new citations were assessed in the same manner as the original search results; that is, by following a three-step winnowing process. This resulted in the inclusion of seven additional studies.

The final sample set included a total of 36 articles, composed of 29 conference papers and 11 journals. These articles are presented in ascending chronological order in Appendix A1. Figure 1 outlines the aforementioned process. A comprehensive list of papers, with justification for inclusion/exclusion

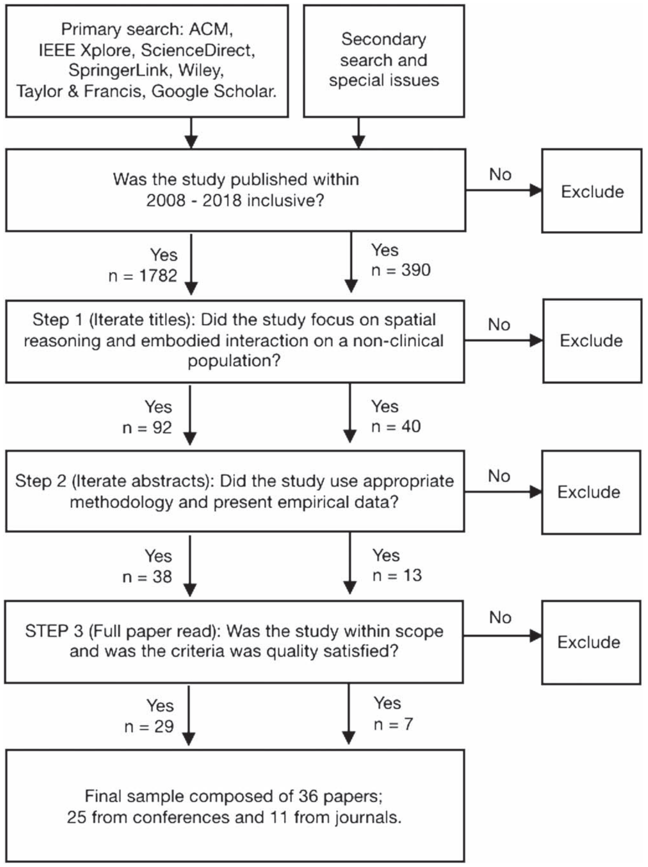

FIGURE 1. The winnowing process adopted by the authors during the primary and secondary search executions of the review protocol.

during the primary and secondary searches, is found in the supplementary online appendix.

4.6. Coding

During the coding phase of the protocol, the team of researchers identified and reported on 13 different variables deemed most critical to addressing the sought-after RQs. The scope of analysis is primarily concentrated on the research design in Ross & Morrison (1996), methodology and data collection instruments, population demographic and sample size, the employed technologies and their broader classification, the realization of an EI and embodiment intervention scale classification (Clifton *et al.*, 2016), the SS engaged, their purpose and skill assessment methods.

Table 4 outlines the variable coding scheme adhered to in this review, by indicating each code with its description and scoring criteria. In cases where a paper reported multiple experiments (Chang *et al.*, 2017b, Jetter *et al.*, 2012, Kasahara *et al.*, 2017, Kruijff *et al.*, 2015, Zhang *et al.*, 2016), data was only extracted from the relevant experiments. If there was more than one relevant experiment (Jetter *et al.*, 2012, Kruijff *et al.*, 2015), data were extracted and coded separately, where applicable. Results from the coding process are presented in Appendix A1.

The coding process was iterative, with regular consensus meetings between the two researchers involved. The primary coder prepared the initial coding in a number of articles and both the authors (coders) had to review and agree in order to reach the final codes presented in Appendix A1. Disagreements between the coders and in-explicit aspects of the reviewed papers were discussed and resolved in regular consensus meetings. Although this process does not provide reliability indices (e.g. Cohen Kappa), it does provide a degree of reliability in terms of consistency of the coding and what Krippendorff (2018) asserts as reliability—‘the degree to which members of a designated community concur on the readings, interpretations, responses to or uses of given texts or data’—as it is accepted in HCI research (McDonald *et al.*, 2019).

5. FINDINGS

After implementing the aforementioned steps, we used non-statistical methods to analyse the data reported in Appendix A1. Before proceeding, it must be mentioned that several studies utilize multiple scoring criteria within a given variable classification, particularly concerning general technology, engaged SS and EI technique.

5.1. Publications

Figure 2 illustrates the distribution of journal and conference publications across the selected years, 2008–2018. The majority of the articles appeared in academic conferences ($n = 25$), with the remainder disseminated as peer-reviewed journal publications ($n = 11$). The studies included in this review span multiple research domains, including but not limited to HCI (Järvinen *et al.*, 2011, Kasahara *et al.*, 2017), VR (Peck *et al.*, 2011, Wang & Lindeman, 2012), robotics (Keren *et al.*, 2012), serious games (Chiu *et al.*, 2018, Freina *et al.*, 2016), educational technologies (Abrahamson & Trninic, 2011, Chiu *et al.*, 2018, Leduc-Mills & Eisenberg, 2011, Lindgren *et al.*, 2016, Wang *et al.*, 2017, Zander *et al.*, 2016), user experience, tangibles (Antle & Wang, 2013), psychology (Larrue *et al.*, 2014) and architectural design (Kim & Maher, 2008). Concerning publication venue (see Table 5), the 36 studies were chosen from 23 different journals and conferences. Not surprisingly, the majority appeared in the conference proceedings for ACM TEI ($n = 4$) and ACM SUI ($n = 4$).

5.2. Research Design, Methods and Demographic

A variety of data collection techniques were employed across the selected studies, as shown at the bottom of Table 6. All but six studies (Jetter *et al.*, 2012, Kitson *et al.*, 2015, Lakatos *et al.*, 2014, Leduc-Mills & Eisenberg, 2011, Ries *et al.*, 2009, Zhang *et al.*, 2016) reflected multiple data input sources, with

TABLE 4. The coding scheme used by the researchers during the data extraction process. Extracted data can be seen in Appendix A1.

Variable	Description	Scoring Criteria
Research design	What research design was used? (Ross and Morrison, 1996)	TE - True experiment QE - Quasi experiment RM - Reseated measures experiment NE - Non-experimental
Research methodology	Type of methodology	QL - Qualitative QT - Quantitative MM - Mixed methods
Data collection	Data collection methods	Report the employed data collection methods
Population	Population demographic	K - Children (under 13) HS - Middle/high school C - Collage/university P - Professional (note profession) A - Adult M - Mixed (write down populations) U - Unspecified
Sample size	Number of particiants	Report the number of participants
Technology	Which technologies used to facilitate embodied interaction?	Report the employed technologies
Technology category	Categorize the type of technologies used to facilitate embodied interaction	H - Handhelds (mobiles, tablets) LTS - Large touch screens DC - Computer MT - Motion tracking IDE - Immersive digital environment VR - Virtual Reality C - Custom
Embodied interaction	How was the embodied interaction realized?	Report the embodied interactive technique
Embodiment intervention scale	Categorize as environmental, figural, vista (Clifton et al. 2016) or a hybrid.	F - Figural V - Vista E - Environmental FV - Figural vistal VE - Vista environmental FE - Figural environmental
Spatial skills	Which spatial skills were targeted?	P - Spatial perception M - Spatial memory N - Navigation O - Spatial perspective/orientation V - Spatial visualization MR - Mental rotation G - General spatial skills
Skills assessment	What was the assessment approach?	$\tilde{A}$ - None Pre - Pre test Post - Post test B - Both
Spatial skills purpose	Did the study enhance or develop the targeted spatial skills?	DG - Development general DS - Development specialized E - Enhancement
Research objective	What did the study investigate?	Write down a summary of the RQs if stated by author, or leave blank

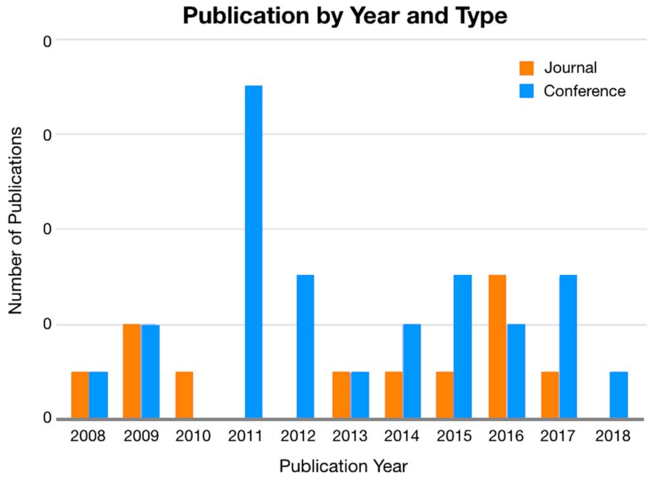

FIGURE 2. Distribution of publications over time.

TABLE 5. Distribution of publications by conference and journal.

Publication Venue	# of Studies
Advanced Visual Interfaces (AVI)	1
Behaviour & Information Technology	1
Human Factors in Computer Science (CHI)	3
Int. HCI and UX Conference in Indonesia (CHIuXiD)	1
Computers in Human Behavior	1
Computers & Education	2
Designing Interactive Systems (DIS)	1
Human–Computer Interaction	1
Interaction Design and Children (IDC)	3
Intelligent Robots and Systems (IROS)	1
Intelligent User Interfaces (IUI)	1
Journal of Cognitive Psychology	1
Journal of Virtual Reality and Broadcasting	1
Games and Learning Alliance (GALA)	1
International Symposium on Smart Graphics	1
Personal and Ubiquitous Computing	1
Spatial User Interaction (SUI)	4
Symposium on 3D User Interface (3DUI)	2
Tangible, Embedded and Embodied Interaction (TEI)	4
Transactions on Computer–Human Interaction (TOCHI)	1
Transactions on Intelligent Interactive Systems (TIIS)	1
Virtual Reality Conference	1
Virtual Reality Software and Technology (VRST)	2

$n = 14$ using at least three different tools. Questionnaires ($n = 18$) were the most popular research instrument, followed by non-spatial skills pre/post assessment ($n = 14$) and video recording ($n = 11$). A noteworthy observation is that 10 studies administered pre-/post- test of SS, one of which also assessed non-spatial abilities (Wang *et al.*, 2017), specifically physics and visual motor integration (VMI). As movement of self is paramount to EI and several of the selected studies include hand movement (Antle & Wang, 2013, Chang *et al.*, 2017a, Chiu *et al.*, 2018, Lakatos *et al.*, 2014, Zaman *et al.*, 2015), it was surprising to discover such a low number of studies taking an interest in their participants VMI abilities. In addition, we note five studies classified as ‘other’, which included manual distance measurement (Ries *et al.*, 2009), a pointing task (Kitson *et al.*, 2015), a reconstitution task (Larrue *et al.*, 2014), map score tests (Wallet *et al.*, 2009) and task switching (Endert *et al.*, 2011).

TABLE 6. Distribution of publications by research design (top), sample population (middle) and data collection instruments (bottom). Note that several studies employ multiple data collection methods.

Research Design	# Studies
True experiment	5
Quasi-experiment	10
Repeated measures	13
No-experiment	8
Sample Population	# Studies
Children	8
Middle & high school	2
University	17
Professional	1
Adult	6
Mixed	1
Unspecified	1
Data Collection Instruments	**# Studies**
Questionnaire	18
Interview	6
Observation audio	6
Observation notes	2
Observation photography	1
Observation video	11
Observation unspecified	3
Data logging	5
Custom software integration	7
Motion sensors	4
Pre/post assessment (non-spatial)	14
Pre/post assessment (spatial)	10
Other	5

5.3. Technologies for Embodied Interaction

The technologies adopted in realizing EI throughout the selected studies were classified into seven technology categories, as outlined in Table 4. For the cases when an experiment used a control, only the technologies required by the intervention were coded. We deem it necessary to outline each technology category to provide additional context to the reader.

TABLE 7. Distribution of publications by technology categories. Note that several studies utilized multiple technologies from different categories.

Technology Category	# of Studies
Handhelds	9
Large touch screens	5
Desktop computer	1
Motion tracking	16
Immersive digital environment	7
Virtual reality	10
Custom	18

TABLE 8. Distribution of publications by embodiment intervention scale.

Scale	# Studies
Figural	14
Vista	3
Environmental	11
Vista environmental	2
Figural environmental	3
Figural vista	4

Handhelds include small computing devices such as cell phones and tablets. *Large touch screens* cover tabletop devices and large interactive screens. *Desktop computer* denotes the use of a desktop computer. *Motion tracking* categorizes all systems with sensors used for tracking a user's movement (i.e. Leap Motion, Vicon Motion tracking, motion tracked gloves, etc). An *immersive digital environment (IDE)* describes immersive systems that do not require virtual reality (i.e. CAVE System, XIM, MEteor and wall projections), whereas interventions that require use of a head-mounted display (HMD) are coded as VR. Lastly, the *Custom* category represents combinations of pre-existing technologies or innovative devices constructed by the researchers for the purpose of their study. Appendix A2 presents a comprehensive mapping between each technology category, its descriptive technologies and the assigned studies.

The most popular technology categories were Custom ($n = 18$), Motion tracking ($n = 16$) and VR ($n = 10$); see Table 7. For the Custom category, researchers presented technologies including but not limited to a wearable puppet suit, interactive floor tiles, sensor-enabled puzzle pieces and wooden blocks, a custom data glove, an elevation-aware backpack, a swivelling chair interface, a human joystick and a modified treadmill. It is worth highlighting that the use of virtual reality was paired with motion tracking in all but two cases (Freina *et al.*, 2016, Marchal *et al.*, 2011) and that motion-tracking devices were always paired with technologies from other categories. Additionally, only eight studies included tangibles as part of the embodied experience.

5.4. Embodiment Intervention Scale

Early works centred on the human psychology of spatial understanding. Montello (1993) theorizes that spatial scale greatly influences how humans understand and manage their surrounding spatial information. Each method for engaging the body can be classified based on a parameter-termed scale, figural, vista, or environmental, as defined by Montello (1993) and then further augmented by Clifton *et al.* (2016). According to Montello, *figural scale* describes the projective space that is smaller than the body it surrounds and includes grasping and moving physical objects or controlling virtual objects as if they were real objects that could be manipulated using the hands. Space that is similar in size to the body it surrounds is termed *vista scale* space. Slight locomotion *may* be required to perceive all of the properties belonging to this space. Lastly, *environmental scale* space exceeds the size of the body it surrounds and requires appreciably large movement for the body to visually consume the entirety of the space (environmental scale requires users to navigate physical or virtual environment (VE) and is connected with large-scale SS).

We classified each study according to the scale of EI within the user's projective/surrounding space, as defined by Clifton *et al.* (2016) (see Appendix A3 for the distribution of publications). Each possible combination of the embodiment intervention scales (figural, vista, environmental, figural vista, vista environmental and figural environmental) was evident among the 36 selected studies. However, both the figural and the environmental embodied intervention classes occurred with much higher frequency than the remaining classes. Figural embodiment interventions (e.g. to perform mid-air hand gestures (Chiu *et al.*, 2018) or to tilt a handheld device (Lakatos *et al.*, 2014)) were the most frequent ($n = 14$). Environmental embodied interventions, in which participants perform physical (Boari & Fraser, 2009, Oulasvirta *et al.*, 2009) or virtual navigation-related tasks (Kitson *et al.*, 2015, Peck *et al.*, 2011), were the second most popular classification ($n = 11$). The remaining studies were almost evenly divided across the alternate categories. See Table 8 for details.

5.5. Distribution of Spatial Skills

With respect to SS classification, seven distinct categories were identified by the selected studies. To avoid engaging in the confusing discourse concerning the definition of SS, when assessing and categorizing our selected studies we classified SS in accordance with nomenclature employed by the paper's authors. We note that we decided to fuse spatial orientation and spatial perspective into a single category (Spatial orientation (O)), as these terms represent the same SS (Dünser *et al.*, 2006).

TABLE 9. Distribution of publications by spatial skills (top) and spatial skill purpose (bottom).

Spatial Skills (SS)	**# Studies**
Navigation	16
Mental rotation	3
Spatial perception	6
Spatial orientation	7
Spatial memory	5
Spatial visualization	3
General spatial skills	8
Spatial Skill Purpose (SSP)	**# Studies**
Development general	5
Development specialized	3
Enhancement	27
Not classified	1

Navigation occurred most frequently ($n = 16$), followed by general SS ($n = 8$), spatial orientation($n = 7$) and spatial perception ($n = 6$). Studies classified as 'general' include concepts and tasks that the researcher described as 'spatial reasoning' (Leduc-Mills & Eisenberg, 2011, Lindgren *et al.*, 2016, Quarles *et al.*, 2008, Roberts *et al.*, 2014), 'geometric thinking' (Keren *et al.*, 2012), proportional reasoning (Abrahamson & Trninic, 2011) and 'spatial problem solving' (Antle, 2013, Antle & Wang, 2013). The remaining skills were few in number, with spatial memory engaged in five studies. Both mental rotation and spatial visualization contained three studies each (see Table 9). The majority of studies ($n = 26$) engaged a single SS, whereas the remaining ($n = 10$) deliberately targeted multiple abilities. The findings also show that spatial memory is always paired with navigation. Appendices A1 and A4 provide in-depth coding of each paper.

Researchers have demonstrated that implementing technology properly enhances not only the experience but also the academic performance (Dix, 1999). Information can be presented in various ways, for example in STEM the required visualization utilizes appropriate technology to enhance conceptual development and enrich understanding. This is demonstrated in our literature review, since the various capacities of technologies were found beneficial for certain SS. For example, designing through 3D software allows users to think visually in three dimensions, which improves their spatial visualization (Kim & Maher, 2008, Wang & Lindeman, 2012). Other technologies such as AR/VR and GPS navigation were able to enhance SS. For example, by visualizing and enhancing images or AR/VR environments provides users with additional information, becoming a new kind of user interface with 3D information that enhances users' shared spatial immersion perspective (Zaman *et al.*, 2015), spatial perception (Ries *et al.*, 2009) and other types of large-scale SS (Leduc-Mills & Eisenberg, 2011). Another noticeable type of technology found to be instrumental in enhancing SS are tangibles and sensor technologies (i.e. haptic feedback, object manipulation) that enable precise monitoring of the position of our body (e.g. finger position), which enhances the experience and helps us to overcome certain limitations of other technologies (e.g. the detection of grasping with Leap Motion can often create frustrating experiences) as well as enhancing motor cognition and other intermediate, vista-scale SS (Quarles *et al.*, 2008). Therefore, understanding the impact of technology (and its affordances) allows us to find the best ways to integrate technology into various contexts (e.g. classrooms, working environments) to enhance users' SS.

5.6. Distribution of Spatial Skills Purpose

Papers were also classified according to how the SS were engaged throughout the study (i.e. their purpose; see Appendix A15). We defined three mutually exclusive codes that categorized each study as either SS development or enhancement. Development occurs when an embodied interactive system aims directly at improving the user's SS. Development is recognized by transferability of skills beyond engagement with the embodied interactive system, such that the newly acquired or enhanced skills propagate into the real world. Though skills development typically entails practice over time, we relaxed this constraint and included non-longitudinal studies that assessed the user's SS after using the EI-based system (i.e. studies that are not conducted over an extended period of time, but still investigate transferability of SS to the real world; Mazalek *et al.* (2011)). Furthermore, studies that outlined a process of creating a tool purposely to develop users' SS (but did not necessarily perform experiments to assess the tool's effectiveness) were also categorized as development (Chang *et al.*, 2017b, Chiu *et al.*, 2018). We sub-divided SS development into the following categories: development of a SS with (i) *general* transferability to the external world (i.e.Development general (DG)) or (ii) targeted transferability to a *specialized* scenario in the external world (i.e. Development specialised (DS)). Five papers were categorized as general SS development, and three as specialized SS development. Enhancement (E) includes studies aimed to amplify performance of a SS; however, the enhancement is not required to be the main focus or end goal of the embodied interactive system. Moreover, the enhancement process does not occur over time. Rather, by mastering engagement with a specific interface or system, the user's SS enhancement is limited to their engagement with the embodied interactive system and does not translate to the real world. A large majority of studies were classified as enhancement ($n = 27$). Note that Kasahara *et al.* (2017) was left unclassified, as researchers agreed that it could not be classified as either SS development or enhancement.

5.7. Research Objectives' Thematics

Researchers explored the relationship between SS and EI from various angles in pursuit of a variety of unique goals, such as direct SS development and enhancement (Chiu *et al.*, 2018, Mazalek *et al.*, 2011, Zander *et al.*, 2016), improved accuracy and realism of immersive experiences (Kitson *et al.*, 2015, Ries *et al.*, 2009) and facilitating collaborative design (Zaman *et al.*, 2015) and animation (Lakatos *et al.*, 2014) tasks. Moreover, upon qualitative assessment of the RQs, five central themes emerged. First, researchers explored the use of tangibles to enrich representation in order to support spatial and non-spatial problem solving. Examples of such research objectives include tangible representation of virtual objects as a means for engaging the motor system in a virtual world to increase embodiment and support SS (Chang *et al.*, 2017a,b). Researchers also focused on the role of avatars to facilitate understanding and manipulate spatial concerns. An example of this is Ries *et al.* (2009)'s investigation into the effects of geometric and motion fidelity of a user's avatar on self-perception, specifically concerning distance estimations, in VR environments. Next, researchers developed tools to help train future employees and support work-related tasks (Kim & Maher, 2008, Lakatos *et al.*, 2014, Quarles *et al.*, 2008, Zaman *et al.*, 2015). There is also an interesting body of research focusing on spatial learning, with children as end-users. These studies involved a diverse collection of EI techniques. For example, Chiu *et al.* (2018) investigated how gestural interaction can help engage children when learning MR, while Wang *et al.* (2017) leveraged a device's tilt-detection ability to support concepts of projectile motion. Lastly, the greatest foci in research trends explored the role of leaning and rotating the body to facilitate or enhance aspects of navigation, for instance how the different navigation modes (translation, rotation) affect the user's experience, spatial memory and sense of presence during navigation in a VE (Järvinen *et al.*, 2011). Larrue *et al.* (2014) examined how the impact of rotation on the transfer of spatial knowledge varies between virtual and physical worlds. Alternatively, Kruijff *et al.* (2015) asked how body tilt affects self-motion perception during navigation tasks in VR environments. Detailed information about each study's research objectives can be found in the last row of Table A1 in the Appendix, along with the EI (in column 7) and SS involved (in column 9).

6. DISCUSSION

After identifying a vast collection of initial studies ($n = 1782$), it can be observed that as a relatively new interdisciplinary field, EI and SS form a growing domain that has gained the attention of researchers interested in diverse areas, including but not limited to, education (Chiu *et al.*, 2018, Keren *et al.*, 2012, Wang *et al.*, 2017, Zander *et al.*, 2016), 3D modelling (Lakatos *et al.*, 2014), interaction design (Järvinen *et al.*, 2011, Kruijff *et al.*, 2015), navigation studies (Boari & Fraser, 2009, Oulasvirta *et al.*, 2009) and general design (Zaman *et al.*, 2015). Through application of our quality and inclusion/exclusion criteria, we selected high-quality studies most relevant to our overarching proposed RQ: *What are the research advancements in the intersection of embodied interaction and spatial skills?* (section 2). This resulted in a distilled selection of $n =$ 36 peer-reviewed studies, which were coded according to a schema developed to address the overarching RQ and the sub-RQs, outlined in Table 4.

6.1. Users and Methods in Embodied Interaction and Spatial Skills Research

The analysis showed that experimental procedure (Ross & Morrison, 1996) (i.e. true experiments, quasi-experiments and repeated measures) was favoured over non-experimental research design. Researchers also predominantly employed quantitative analysis to assess their work. Several of the selected studies compared a traditional interface and its embodied counterpart to investigate the potential benefits of the EI capacities to develop or enhance SS (Antle & Wang, 2013, Chiu *et al.*, 2018, Freina *et al.*, 2016, Kitson *et al.*, 2015, Wang *et al.*, 2017). Research on the intersection of EI and SS focuses on 'artefacts-centred evaluations' (papers exploring the application of an EI capability to enhance or develop a particular, or set of, SS) and, sometimes, might fail to look beyond particular artefacts in order to develop intermediate-level knowledge. Research works in the area of EI and SS are connected with the increasing body of work in theories of embodiment, which focuses on how practical engagement and the structure of the body shape perception, experience and cognition (Antle *et al.*, 2011, Marshall, 2007). Most of them reject a view of human cognition grounded solely in abstract information processing (Marshall, 2007). Also, as we identified in our literature review, EI is increasingly used in the design, analysis and evaluation of interactions with and around technology. Seminal works on EI include a CHI workshop (Antle *et al.*, 2011) where several participants discussed how EI has developed in the decade since the foundational work of Dourish's *Where the Action Is* (Dourish, 2004). As we can see from this literature review, the benefits of EI are evident in the methodologies of the papers included. Several of the methodological aspects have been expanded significantly in recent years with the development of a range of technologies designed to sense movements of the body and utilize ubiquitous computing infrastructures to employ contextual data.

However, although stemming from years of research in EI and SS as individual domains, the overlap of EI and SS is a newly unfolding research domain and its underpinning theories are under-developed. Before researchers can begin to develop theorems that establish the field, much exploratory work is needed to uncover the axioms that define its foundation. Disregarding the richness offered by alternate research designs (i.e. non-experimental) and qualitative methodologies (i.e. stand alone or mixed methods) in favour of a *de facto* quantitative experimental approach may prevent researchers from harnessing their full potential to advance the nascent domain.

A qualitative approach (stand alone or mixed methods) may offer greater opportunities for understanding the impact that EI has on the enhancement and development of SS, especially from a user experience perspective. Furthermore, Creswell & Plano Clark (2011) highlight numerous benefits to using mixed methods, which appeared throughout the selected studies, such as triangulation of data (Antle & Wang, 2013, Kruijff *et al.*, 2015) and investigation of multiple hypotheses in a single study (Chiu *et al.*, 2018, Zaman *et al.*, 2015).

Research on the intersection of EI and SS employed mixed methods to quantitatively evaluate SS, while qualitatively assessing participants' physical behaviour (Boari & Fraser, 2009, Larrue *et al.*, 2014, Oulasvirta *et al.*, 2009) or verbal opinions (Chiu *et al.*, 2018, Kitson *et al.*, 2015) in response to an embodied interface. Studies that used purely qualitative methodologies were few in number and mainly explored the intricacies of participant behaviour through observational (i.e. audio, video and notes) transcript analysis, and in cases where conducting quantitative analysis was not a suitable measure from which to address the researchers' objectives (Kasahara *et al.*, 2017, Keren *et al.*, 2012, Lakatos *et al.*, 2014).

Regarding the user groups employed in EI and SS research, almost half of the studies were performed on university students (Antle & Wang, 2013, Endert *et al.*, 2011, Jetter *et al.*, 2012, Kim *et al.*, 2010, 2015, Kitson *et al.*, 2015, Lakatos *et al.*, 2014, Larrue *et al.*, 2014, Wallet *et al.*, 2009, Zhang *et al.*, 2016), with particular focus on computer science and STEM undergraduates (Boari & Fraser, 2009, Chang *et al.*, 2017a,b, Palleis & Hussmann, 2016, Ries *et al.*, 2009, Wang & Lindeman, 2012). This is mostly likely attributed to ease of participant accessibility; however, it might introduce participant bias, since it is likely that college students are more familiar with EI-based technologies and they are already trained in some SS (e.g. STEM students). According to Wai *et al.* (2009), SS are a precursor for success in academics and professions in STEM. Therefore, it can be concluded that a STEM-focused demographic presumably demonstrates heightened capabilities in SS tasks and understanding, thereby weakening the generalizability of the studies' results to the general population. Similarly, two studies exclusively used male participants (Järvinen *et al.*, 2011, Oulasvirta *et al.*, 2009) and previous literature suggests that males outperform females in various SS (e.g. mental rotation; Terlecki *et al.* (2008)). Lastly, despite the body of evidence supporting EI-based learning (Abrahamson & Trninic, 2011, Lindgren *et al.*, 2016), and the fact that 'spatial ability plays a critical role in structuring educational and occupational outcomes in the general population' (Wai *et al.*, 2009), eight studies centred on children (i.e. younger than 13 years) and two on middle/high schools student (Leduc-Mills & Eisenberg, 2011, Wang *et al.*, 2017). Increasing EI-based SS interventions targeting adolescents might have the potential to stimulate interest in spatial concepts and nurture spatial abilities, which could potentially lead individuals towards higher education and professions in STEM domains.

6.2. Realizing Embodied Interaction

In this section, we discuss how the most frequently utilized technologies (i.e. technology categories) and users' physical actions were employed to establish meaningful communication between the user and the machine.

6.2.1. *Capacities of motion tracking*

EI describes the use of movement to convey meaningful communication between a user and a technological system (Dourish, 2004). Not surprisingly, this makes motion-sensing devices (e.g. Leap Motion (Chang *et al.*, 2017a,b, Chiu *et al.*, 2018, Zaman *et al.*, 2015), OpiTrak Motion Capture (Kasahara *et al.*, 2017, Larrue *et al.*, 2014), Microsoft Kinect (Zhang *et al.*, 2016), etc.) an attractive choice for supporting EI in SS research. The dominant presence of motion sensing might be attributed to the ability to capture a wide variety of users' physical actions performed across a vast amount of space, which gave researchers ample creative opportunities when establishing communication between user and system. From an embodiment intervention scale perspective, motion sensing was used to capture hand gesture and position (Chiu *et al.*, 2018, Lakatos *et al.*, 2014, Zaman *et al.*, 2015) performed in projectively small surrounding space (i.e. figural scale) addressing mainly small-scale SS. Conversely, it was also used to recognize larger full-bodied interactions, such as locomotion (Järvinen *et al.*, 2011, Kruijff *et al.*, 2015, Larrue *et al.*, 2014, Peck *et al.*, 2011), that occurred over larger distances (i.e. environmental scale). In some cases, augmenting pre-existing technologies with motion-sensing capacity facilitated EI through a range of new movements and in new embodiment intervention scales. For example, the use of motion tracking when users observe their avatar's movement during navigation (Kasahara *et al.*, 2017, Ries *et al.*, 2009) introduces environmental scale to otherwise strictly vista scale interactions, resulting in vista environmental scale EI. Other research (Kim *et al.*, 2010, 2015) integrated motion tracking of figural small-scale hand movements used to navigate VEs, resulting in figural environmental scale interactions. Besides their direct implementation, motion-tracking technologies were also utilized in combination with additional technologies (e.g. VR (Kruijff *et al.*, 2015, Peck *et al.*, 2011) or wearable (Lakatos *et al.*, 2014)) to decrease the frustration of the user, enhance user understanding of their spatial relationship to their surrounding environments (Ries *et al.*, 2009), facilitate manipulation of virtual objects (Chiu *et al.*, 2018), make a device smarter (i.e. take into consideration users' body placement (Lakatos *et al.*, 2014)) and add an affordance or interaction capacity (e.g. detection of user movements (Kruijff *et al.*, 2015, Lindgren *et al.*, 2016)). Collectively, the aforementioned examples illustrate one of the most important advantages of sensing and motion tracking in EI and SS research: namely, motion tracking's ubiquitous nature and ability to cascade with almost everything else (with a tendency toward IDEs and VR systems).

6.2.2. *Motion tracking to support mid-air hand gestures*

Motion tracking facilitated the use of mid-air hand gestures as input to handheld devices (Lakatos *et al.*, 2014), desktop computers (Chiu *et al.*, 2018) and in VR systems (Zaman *et al.*, 2015). For example, Chiu *et al.* (2018) took the standard approach of using Leap Motion to capture a user's gesture to rotate on-screen objects while maintaining congruency between the user's hand movement and the spatial concept to be mastered (i.e. mental rotation). Alternatively, Lakatos *et al.* (2014) leveraged motion tracking to enhance a device's capacity to detect the spatial placement of a user's hand relative to the augmented device (i.e. added spatial awareness of a user's hands). The space around the handheld device was divided into three domains, each of which supported its own set of interaction techniques to instruct separate device functions. Zaman *et al.* (2015) attached Leap Motion devices to a pair of synchronized VR HMDs, to offer a single shared perspective to remote collaborators. Hand movement was tracked and made visible in each HMD from a single point of reference, illustrating the capacity of hybrid motion tracking and VR systems to enable shared experiences.

6.2.3. *Motion tracking to support tangibles, locomotion and avatar control*

Motion sensing was also used to support locomotion both actively and passively. Actively, it realized control mechanisms that leveraged changes in the user's body position to communicate navigational needs, such as changes in direction and velocity (Kruijff *et al.*, 2015, Wang & Lindeman, 2012). Specifically, leaning-based interfaces required users to shift their body weight while seated (Kruijff *et al.*, 2015) or standing (Wang & Lindeman, 2012), in a fixed location, to instruct travel through an environment viaVR HMD. In practice, the visuals supplied by the VR HMD, updated in response to users' leaning motions, simulating the sensation of moving through space. As recommended by Chiu *et al.* (2018), researchers maintained leaning congruency while mapping leaning direction to increases in travel velocity (i.e. leaning more forward instructed travel at greater speeds (Kruijff *et al.*, 2015)). From a passive stand-point, motion sensing devices detected users' change in location as they moved through tracked environments (i.e. VR and IDEs). In this way, users were provided with the opportunity to embody the concepts they were tasked to master. For example, in Lindgren *et al.* (2016)'s MEteor system, children experienced how elements in space establish and maintain orbital paths by enacting the role of an asteroid and traversing through space in accordance with their perceived gravitational forces imposed by dynamic surrounding moons and satellites projected onto the floor in an IDE. Lastly, motion tracking was used to strengthen and manipulate users' relationship with their self-representing avatars by projecting user movement onto the avatar (Kasahara *et al.*, 2017, Ries *et al.*, 2009). Kasahara *et al.* (2017) demonstrated how manipulating the spatial temporal characteristics affects users experience and on self perception.

6.2.4. *VR and IDEs*

Two popular technologies exploited by researchers to realize EI and SS were VR and IDEs (see Appendix A1). Both technologies demonstrate the capacity to facilitate computing experiences that realistically simulate how we experience the real world, which in turn can encourage interaction through explorative (Järvinen *et al.*, 2011) or prescribed sets of user movements (Kim *et al.*, 2015). The affordances demonstrated by VR and IDEs are defined by the projective size of the simulated environment and the physical actions that the VE facilitates or constrains. Unsurprisingly, due to their inherent flexibility, these two technologies support the full spectrum of embodiment intervention scales as illustrated by Kim *et al.* (2015)'s finger-walking-in-place (FWIP) navigation approach (i.e. figural; see later discussion), Ries *et al.* (2009)'s avatar observation at varying levels of geometric and movement fidelity (i.e. vista) and Järvinen *et al.* (2011)'s rotational and translational full-body walking techniques (i.e. environmental).

Moreover, when augmented with motion tracking, VR and IDE technologies support creative and full-bodied expression of user movement. This enables users to become completely immersed in the concepts they are engaged with by allowing them to act as conceptual elements themselves, thereby exercising embodied representational significance through their own body's movement and spatial interactions (Lindgren *et al.*, 2016). Additional benefits of such systems derive from increased physical activity and enriched interaction exchange between user and computing system, which finds benefit in learning and affective engagement (Lindgren *et al.*, 2016).

Furthermore, VR affords researchers the opportunity to generate virtual scenarios that may otherwise be impossible to mimic in real- or mixed-world reality, specifically concerning the engagement and activation of SS. For instance, Freina *et al.* (2016) used a VR HMD to explore how different levels of immersion might enhance a users' spatial perspective talking ability by providing the user with different visual frames of reference. Similarly, Zaman *et al.* (2015) enabled collaborators to share a common spatial perspective through VR HMD while working on a joint design task. Both of these EI-based interventions relied on the affordances of VR to provide the user with a visual view through someone else's eyes (either their collaborator or an non-player character (NPC)).

Lastly, researchers used VR to provide user's with visual cues to manipulate their behaviour in VEs. Kasahara *et al.* (2017) explored the malleability of embodiment by exposing participants to spatial-temporal deformations of a virtual self-avatar to evaluate participants' sense of spatial perception during a movement exploration session; whereas Marchal *et al.* (2011) and Kruijff *et al.* (2015) separately investigated how interaction mappings between VR visuals and user movement (i.e. standing and leaning, seated and rotating) might facilitate use of embodied locomotion interfaces. These examples demonstrate VRs diverse range of affordances, which contribute to it's potential as a principal technology for supporting EI-based interventions. Lastly, both VR and IDEs also readily combine with a host of additional technologies, such as tangibles (Chang *et al.*, 2017a, b), motion tracking (Järvinen *et al.*, 2011, Kasahara *et al.*, 2017, Ries *et al.*, 2009, Zaman *et al.*, 2015) and being integrated into custom devices (Kitson *et al.*, 2015, Kruijff *et al.*, 2015, Marchal *et al.*, 2011, Wang *et al.*, 2007), in order to support new forms of EI to engage the user.

6.2.5. *Handheld devices*

Another technology that has been heavily employed in EI and SS research is handheld devices (see Appendix A1). Nowadays, mobile phones and tablets enable the manipulation of on-screen objects through figural scale actions, such as multi-touch gestures (i.e. swiping, tapping and pinching actions). These devices are also embedded with various sensors (e.g. accelerometers, GPS) that afford context awareness and enable smart detection of the user state (i.e. smart physicality). Researchers exploited these capacities by enabling devices to understand participants' movements, which were then leveraged to help users complete tasks more fluidly (Lakatos *et al.*, 2014, Wang & Lindeman, 2012).

Handheld devices also cascade with additional technologies, such as motion tracking (Kim *et al.*, 2010, 2015, Lakatos *et al.*, 2014, Wang & Lindeman, 2012), IDEs (Kim *et al.*, 2010, 2015), VR (Wang & Lindeman, 2012) and various miscellaneous forms, such as the Wii Fit balance board (Wang & Lindeman, 2012) and RFID tracking (Roberts *et al.*, 2014). These technologies enable EI to occur on a much larger spatial level (specifically environmental) (Kim *et al.*, 2010, 2015, Wang & Lindeman, 2012). For example, in numerous studies, handheld devices were used to support locomotive actions, resulting in a hybrid figural environmental scale. The affordances of multi-touch were used as control mechanisms for navigation (Kim *et al.*, 2010, 2015, Wang & Lindeman, 2012), and various embedded sensors (i.e. accelerometer, GPS), facilitated interactions between users and their surrounding space as they virtually moved throughout large environments as directed by small figural scale interactions, such as tilt (Wang & Lindeman, 2012, Wang *et al.*, 2017) and the FWIP technique (Kim *et al.*, 2015). In sum, due to their ability to seamlessly blend with alternate technologies, handheld devices are appropriate for small- and large-scale EI-based interventions.

6.2.6. *Custom*

Half of the studies were classified as 'custom' technologies (see Appendix A2). This high frequency documents a strong trend for researchers to innovate or combine pre-existing technologies in order to assess how the characteristics of an interaction mapping support spatial concerns. From this we draw two conclusions: (i) researchers need technologies that offer a more complete or holistic approach to engaging the body and (ii) researchers are looking to combine different technological solutions and merge the affordances offered by these technologies, in order to achieve their goals.

6.2.7. *Tangible user interfaces*

A surprisingly low number of studies employed (see Appendix A2). TUI invite the user to grasp, touch and manipulate physical artefacts that represent digital data (Ullmer & Ishii, 2000), thus requiring active engagement of the user's motor-cognitive system. Prior research suggests that use of the hands significantly contributes to the advancement of thinking skills (Klemmer *et al.*, 2006) and might help reduce cognitive load during problem-solving experiences (Goldin-Meadow, 2005). Paired with the benefits of haptic direct manipulation and lightweight interaction (Hornecker & Buur, 2006) offered by tangibles, this may foster new spatial problem-solving strategies, as suggested by Antle & Wang (2013).

Furthermore, TUI offer affordances when used as physical representations of virtual objects within a problem space, as seen in numerous studies (Antle, 2013, Antle & Wang, 2013, Chang *et al.*, 2017a, b, Kim & Maher, 2008). For example, they aid the user in externalizing ideas by providing props that support discussion (Hornecker & Buur, 2006). This is beneficial in single learner (Abrahamson & Trninic, 2011) and collaborative environments (Kim & Maher, 2008). The works of Antle (Antle, 2009, 2013, Antle & Wang, 2013) suggest that in the context of children, direct handling of tangible manipulatives may support the development of mental problem solving strategies through the facilitation of exploratory and direct actions (i.e. less trial and error). When given tangibles to solve a spatial problem (i.e. a puzzle piece), children might have transferred elements of the visualization process to exploratory physical actions using the tangible objects. The physical strategies enabled by the tangibles lessened the need for mental processing, resulting in amplified cognitive performance. This led to to fast and easier spatial problem solving experiences. Moreover, Chang *et al.* explored VR-TEI unification in a VR game purposed to develop spatial perspective skills (Chang *et al.*, 2017a,b). The physicality offered by the tangible expression (i.e. wooden blocks representing a virtual fence) and the tight coupling of mental and physical user interactions supported the user through spatial problem solving tasks by way of EI. Together, these studies demonstrate the powerful role that TUI play when used to augment virtual spaces. Thus, we reinforce the works of Clifton *et al.* (2016) by highlighting the integration of tangibles and physical movement as an untapped resource that warrants the attention of future research, especially for realizing EI in immersive computing environments (i.e. AR, MR, VR).

6.3. **Distribution, Purpose and Assessment of Spatial Skills**

6.3.1. *Distribution of spatial skills*

The selected studies contain a rich distribution of SS (see section 5.5). Moreover, many interventions deliberately targeted multiple abilities. Navigation was the most frequently engaged SS. This might be attributed to the fact that this large-scale SS (Hegarty & Waller, 2005) can be supported by users' embodied actions on the figural (Kim *et al.*, 2010), vista (Zhang *et al.*, 2016) and environmental scale (Boari & Fraser, 2009, Peck *et al.*, 2011), leaving researchers' curiosity ample room explore and experiment. Additionally, all studies focused on spatial memory were centred on navigation. In particular, the partnership between spatial memory and navigation occurred in two ways. First, the user navigated a computing system with physical actions performed via hand movement (e.g. using multi-touch) on an LTS (touch screen or tabletop) (Jetter *et al.*, 2012, Palleis & Hussmann, 2016). These types of interventions relied on small-scale actions to address the large-scale navigation skills. Second, the user navigated a simulated environment with physical actions performed by the whole body, directing locomotion (e.g. walking) (Järvinen *et al.*, 2011, Larrue *et al.*, 2014, Oulasvirta *et al.*, 2009). Here, the embodied intervention was conducted on a large environmental scale. Accordingly, we identify a gap in the EI research targeting spatial memory, since it is addressed only in conjunction with navigation.

Spatial orientation and spatial perception were two other frequently engaged SS. Movement is inherently spatial. Each action performed alters the user's spatial relations and associations (i.e. spatial orientation, spatial perception) to their surrounding environment (Clifton *et al.*, 2016, Uttal *et al.*, 2013), reinforcing the significance of these SS. Thus, it is no surprise that these skills were engaged at a high rate and often involved movement across a large-scale environment (Kasahara *et al.*, 2017, Kitson *et al.*, 2015, Kruijff *et al.*, 2015, Oulasvirta *et al.*, 2009, Ries *et al.*, 2009, Wang & Lindeman, 2012). Furthermore, extensive efforts have been invested in researching the role of spatial orientation in VR (particularly understanding users' difficulty in spatially orienting themselves), emphasizing the tightly coupled nature of the two elements (Riecke, 2003, Riecke *et al.*, 2010, 2007, 2002). Hence, as VR was one of the predominantly employed technologies, we find the prevalence of papers relating to spatial orientation and spatial perception quite fitting. An indicative example from our studies is Wang & Lindeman (2012), who investigated a leaning platform that allowed users to navigate with a flying surfboard interface using two different stances (e.g. frontal and sideways). The employed assessment mechanisms were standardized tests ratings, spatial orientation, understanding of the VE and task performance.

An interesting observation is that although mental rotation was employed in only three studies, the involved EI mappings required the user to interact in completely different ways: first the rotation of entire body positioning to match a virtual avatar (Mazalek *et al.*, 2011), then rotation of an object on screen via mid-air hand gestures (Chiu *et al.*, 2018) and the last study utilized rotation of an object on-screen via multi-touch (Zander *et al.*, 2016). Each study involved hand movements (figural scale), with Mazalek *et al.* (2011) involving a larger projective space surrounding the user and thus involving blended figural vista scale physical actions. Consequently, in the context of EI and SS, the related work has primarily focused on small EI (figural scale) to support MR (small-scale SS). The potential reasoning for this might be the inherent connection between MR and figural scale EI. Furthermore, the complexity of MR required the user to have a full overview of the targeted object and their surrounding environment. This is not always possible in the case of large embodied interventions (environmental scale).

6.3.2. *Spatial Skills Purpose*

Each paper was classified according to how users' SS were engaged throughout the study (i.e. SS purpose), resulting in categorization as either *enhancement* or *development* (see Appendix A5). The majority of researchers addressed ways in which EI enhanced users' SS. These types of interventions promoted users' spatial experience in real time through interaction with an EI-based system. Yet the resulting heightened spatial ability did not transfer beyond users' engagement with the intervention. For example, Endert *et al.* (2011) translated users' natural chair action to facilitate cursor movement, contributing to more fluid cursor navigation across large-scale high-resolution displays.

An important strand of prior research underlines the importance of SS to enable STEM academics and professions (Wai *et al.*, 2009). However, despite this potential motivation to identify and nurture SS, relatively few interventions focused on the general development of SS, specifically concerning traditional educational settings (i.e. the school environment) (Abrahamson & Trninic, 2011, Chiu *et al.*, 2018, Keren *et al.*, 2012). EI is a powerful tool for knowledge acquisition (Lindgren & Johnson-Glenberg, 2013) and embodied play has been shown to support the activation and development of spatial thinking (Baykal *et al.*, 2018, Keren *et al.*, 2012). Moreover, research suggests that some targeted SS are receptive to training through EI tactics, such as congruent gesture (Chiu *et al.*, 2018, Ping *et al.*, 2011) and tangible manipulations (Chang *et al.*, 2017a). Nevertheless, the studies specifically targeting SS development with general transferability to the external world were few in number (Abrahamson & Trninic, 2011, Chang *et al.*, 2017a, Chiu *et al.*, 2018, Keren *et al.*, 2012, Mazalek *et al.*, 2011). Perhaps due to the prematurity of this novel field, it is simply too early to develop comprehensive SS training mechanisms based on EI, and researchers must focus first on determining the EI mappings that effectively and efficiently activate and engage SS prior to attempting to establish such technologies.

6.3.3. *Spatial skills evaluations and assessment*

SS evaluation and assessment played an important role in the selected studies, with researchers utilizing various procedures that relied on user body movement (e.g. finger pointing (Kitson *et al.*, 2015)) and conventional paper-and-pencil methods (e.g. map sketching (Wallet *et al.*, 2009), and standardized tests).

For example, Kitson *et al.* (2015) used a pointing task to assess spatial orientation subsequent to participant exposure in a navigational chair interface. In conjunction with spatial pre-assessments of mental rotation and spatial memory, the pointing method was also utilized by Oulasvirta *et al.* (2009) to evaluate how SS expertise supports human understanding of mobile maps with different dimensional characteristics. The pointing method is especially interesting as it engages SS on multiple fronts. First, pointing is a spatial gesture, through which the user's movement impacts their spatial orientation and perception with elements in their surrounding environment. Second, in each of these studies, pointing was exercised to complete a spatial task. As noted by Hegarty *et al.* (2006), assessment of SS primarily occurs on a figural scale, via paper-and-pencil. So although we deem methods that engage the body in the assessment of SS to be a compelling approach, we are not surprised to find very few of the selected studies employing a movement-based assessment approach.

Conversely, the primary assessment technique was SS standardized paper-and-pencil tests (Chang *et al.*, 2017a, Kim *et al.*, 2015, Larrue *et al.*, 2014, Oulasvirta *et al.*, 2009, Quarles *et al.*, 2008, Wallet *et al.*, 2009, Wang *et al.*, 2017). This is unsurprising, as pre-post tests are a highly common practice in the learning sciences, cognitive science and psychometrics. Of the five distinct SS that researchers assessed (spatial visualization, spatial memory, spatial orientation, mental rotation and navigation), spatial orientation was the most frequented by researchers, albeit no single standardized test can claim dominance due to the vast range of targeted SS and corresponding means of assessment identified in the selected studies. Pre-tests were used as a basis to balance groups in experimental design (Kim *et al.*, 2015) and assess the effects of proprioceptive information on the transfer of spatial learning between virtual and physical realities (Larrue *et al.*, 2014). Additionally, they also supported researchers in investigating how the interplay between SS expertise (specifically, spatial visualization, spatial orientation) and embodied physics simulation influenced students' conceptual understanding of projectile motion (Wang *et al.*, 2017).

Although standardized tests have the capacity to provide validity and allow researchers to compare across conditions (e.g. paper-based and technology-based interventions) and across settings and contexts (e.g. school, museum, home), they fail to capitalize on recent developments in sensing and ubiquitous technologies. We conclude that further research is needed to identify the connections between the tested SS and the data resulting from EI experiences. This might enable researchers to develop more advanced and automated assessment techniques that utilize ubiquitous technologies and analytics (e.g. how data from various sensors can aid researchers in assessment of SS). Moreover, such developments might also expand research in EI and SS by propelling researchers and practitioners to explore the effectiveness of different embodied mechanisms and interfaces in a relatively easy, agile and temporal manner.

6.4. Embodied Interactions's Capacity to Support Spatial Skills

Our final research question (RQ4) was broken down into two sub-questions. Specifically, how did researchers leverage EI to enhance or develop SS, and what are the implications for research and practice? To address these concerns, we synthesize the results of the papers included, and discuss the most dominant research themes presented in the findings (section 5.7, Research Objectives' Thematics). We identify three capacities of EI that researchers can leverage when designing EI experiences to support SS: namely, EI's capacities for (i) enrichment, (ii) convergent smart physicality and (iii) transferability. Lastly, we highlight how these capacities have been used in practice and underline important implications and design considerations with the aim of guiding research and practice.

6.4.1. *Leveraging tangibles to influence spatial skills*

An important research theme in the literature involved the use of tangibles to realize EI for supporting SS. This topic been discussed in section 6.2.7, where we emphasized the affordances of using TUI as physical representations of virtual objects. In this regard, tangible EI enriches the user's perceptual understanding of the spatial relationships between problem elements (i.e. spatial perception) (Kim & Maher, 2008), a characteristic of EI that we refer to as *the capacity for enrichment*. As proposed by Kim & Maher (2008), this enriched understanding of spatial relationships quite possibly results from the user having having access to multiple object representations (i.e. digital and physical). This notion of enrichment is closely associated with transhumanist technologies (Eisenberg, 2017) that can enable users to perceive important insights that can augment their (among others, spatial) capacities (just as the telescope is a form of enrichment to our vision and enables us to see the heavens).

Another affordance of tangible EI for developing and enhancing SS (e.g. spatial visualization, spatial orientation) is the *capacity for convergent smart physicality*. Convergent smart physicality can be described as the combined intelligence and physicality of interaction objects (i.e. a tangible or user environment): that is, the interaction object's ability to detect information regarding user state through user-device interaction and to harness this information to assist the user in achieving the current task. In several studies, the researchers leveraged tangibles' capacity for convergent smart physicality (Lakatos *et al.*, 2014, Roberts *et al.*, 2014, Wang *et al.*, 2017, Zaman *et al.*, 2015, Zhang *et al.*, 2016). For example, Wang *et al.* (2017) evaluated how the conjunction of a tilt-aware tablet and students' spatial visualization and orientation abilities affected their understanding of kinematic concepts in a high school physics setting. A similar intervention was explored by Lakatos *et al.* (2014), who used a custom data glove and spatially aware tablet to remodel and enhance collaboration between animation designers.These researchers exploited the natural capabilities of the tablet to activate the users' spatial thinking through EI, thus demonstrating the untapped potential of the physicality and embeddedness of these devices to engage SS through movement.

This is in line with previous research in the area of TUI (Benford, 2005, Hornecker & Buur, 2006, Price & Rogers, 2004) that demonstrates how they encompass a broad range of systems and interfaces relying on EI, manipulation, physical representation, and embeddedness (e.g. of sensors) by augmenting both digital and physical spaces (Benford, 2005, Hornecker & Buur, 2006, Price & Rogers, 2004). We see that the findings of our literature review in the context of EI and SS can be conceptualized in the Tangible Interaction framework proposed by Eva Hornecker (Hornecker, 2004, Hornecker & Buur, 2006). This framework consists of four themes: namely, tangible manipulation (i.e. material representations), spatial interaction (i.e. embeddedness of tangible interaction that depends on interactive movement), embodied facilitation (i.e. how the configuration of objects and space affects or governs user behaviour) and expressive representation (i.e. material and representations employed by TUI). Hornecker & Buur (2006)'s framework provides a means for categorizing the capacities of tangible interactions and is thus highly relevant to research exploring the capacities of EI to support SS, particularly due to its focus on the social aspects of EI and tangibility.

Lastly, we underline that current educational software solutions are under-utilizing the full capabilities of tablets and tangibles by ignoring the combined potential of physicality (e.g. touch screen abilities) and intelligence (e.g. embedded sensors such as gyroscopes and motion and light sensors) (Wang *et al.*, 2017). Researchers need to push beyond the normative uses of such devices in the pursuit of fostering the EI affordances capable of activating SS.

6.4.2. Movement for navigating virtual environments

Another prominent theme in the selected studies was how EI facilitates various aspects of navigation in VEs (e.g. IDEs, VR). Researchers investigated the influence of rotational embodied movement on the transfer of spatial knowledge between virtual and real worlds (Larrue *et al.*, 2014), as well as its effect on spatial memory (Järvinen *et al.*, 2011). They also compared different movement-based navigational instruction techniques (i.e. FWIP) against traditional methods (i.e. mouse, keyboard, joystick) to assess the impact on spatial knowledge acquisition (Kim *et al.*, 2010, 2015). Moreover, several studies under this theme explored EI to direct locomotion via leaning (Kruijff *et al.*, 2015, Marchal *et al.*, 2011, Wang & Lindeman, 2012) and rotating (Järvinen *et al.*, 2011, Kitson *et al.*, 2015) the body while the user was standing or seated.

Researchers found that passive navigation through an environment, such as observing the visual flow of movement from a first-person perspective, is not enough to facilitate the transfer of spatial learning between virtual and real worlds. Furthermore, rotational body movement, such as turning one's head in order to navigate a VE, as well as vestibular information, is necessary to catalyse an exchange of spatial knowledge between realities (Larrue *et al.*, 2014). We refer to EI's ability to transfer spatial knowledge between the virtual and real worlds as its *capacity for transferability*. This affordance enables a researcher to take advantage of many elements of a user's sensorimotor system in ways that traditional interaction cannot (e.g. moving our bodies in and through space, seeing spatial properties and relations, feeling them with our hands) in the pursuit of enhancing SS. Moreover, numerous navigation-based studies (Kitson *et al.*, 2015, Kruijff *et al.*, 2015, Ries *et al.*, 2009) demonstrated that EI's ability to enrich users' spatial perception (i.e. capacity for enrichment) allows the user to receive and process additional information that amplifies their SS (e.g. capturing useful information utilizing sensors and providing a number of useful cues to human sensorimotor systems).

The above illustrates the importance of user-performed movement to the spatiality of navigational tasks. However, not all movement is good movement when it comes to immersive navigation. Järvinen *et al.* (2011) demonstrated that *too* much rotational variance during navigation has the capacity to hinder spatial memory performance. When EI requires a user to heavily exaggerate a characteristic of movement, that movement may become misaligned with its real-world counterpart. This opposes the natural advantages offered by EI, by working against the user's instinctive understanding and expectation of those movements. Consequently, in these scenarios, users may experience feelings of increased cognitive load, as reported by Järvinen *et al.* (2011) and Kruijff *et al.* (2015). Furthermore, the work by Kruijff *et al.* (2015) reinforce the importance of action-perception coupling while simultaneously emphasizing the dynamism of the movement involved. They showed that static forward leaning while sitting during an immersive navigation task enhanced users' sense of forward self-motion; however, surprisingly, dynamic leaning does not yield the same effects. Kruijff *et al.* (2015) speculated that excess movement induced cognitive load, thereby detracting from the user experience. That being said, this does not restrict navigation-related EI mappings in VEs to the usual modes of transportation (i.e. walking) in order for them to be effective transmitters of spatial knowledge. The action-transfer design approach, presented by Kim *et al.* (2015), demonstrates the efficacy of 'walk-like' navigation techniques for virtual worlds, such a FWIP and full-body Walking-In-Place (WIP). The consequences of these novel techniques are far reaching, with design implications for supporting spatial learning when faced with limited room to operate, as well as for persons with reduced or compromised mobility capacity, as pointed out by Kim *et al.* (2015).

Collectively, the aforementioned research shows that when considering an EI approach for navigational strategies in VEs, movement matters. Moreover, by maintaining a high degree of congruency between the user's performed action and its induced response, stakeholders (e.g. researchers, interaction designers) can leverage the built-in benefits of EI (i.e. capacities for transferability and enrichment) to support immersive navigation experiences from a variety of angles (e.g. spatial perception, spatial knowledge transfer and spatial memory). Yet the bulk of the studies that addressed this theme focused on enhancing SS (i.e. improving or easing the user's immediate spatial experience) rather than developing the user's SS in the long term. Investigating the role of EI in developing SS requires more complex and longitudinal studies, compared to the ones that address enhancement; this may be the reason that such little emphasis has been placed on SS development in VR systems. Previous work has focused on spatial image schemas (Macaranas *et al.*, 2012) and 'spatial updating' (Riecke *et al.*, 2005). Spatial updating refers to the process of automatically amending the mental representation of our surroundings, which contributes to how users experience spatial orientation and spatial perception. Spatial updating is extremely powerful for users' SS development and occurs in the absence of physical motion (e.g. visual information from a known scene alone can, indeed, be sufficient (Riecke *et al.*, 2005)). In the same vein, previous works have focused on embodied conceptual metaphors as cognitive mechanisms underlying intuitive interaction in direct interactional computational systems (Antle *et al.*, 2009a, Hurtienne *et al.*, 2010). These works highlight the difference between EI mapping for controlling a system and mapping action to representations. It is important to exploit this difference to provide the necessary scaffolding for learning (e.g. help the user understand/learn about spatial and/or related abstract concepts). Additionally, Kimura *et al.* (2017) suggest that VR's lack of spatial cues may override its capacity to properly facilitate spatial cognitive development, as a spatial cues deficit may cause less accurate encoding of VEs compared to real-world environments. In turn, this may render VEs unsuitable for the development of spatial cognitive research.

6.4.3 Embodied interaction and children's spatial skills

The final theme that we address is the use of EI to develop children's SS, and its potential to transform STEM education. In section 6.2.7 we discussed many benefits of using tangible EI to serve as physical representations of virtual objects. Regarding children's education, researchers (Abrahamson & Trninic, 2011, Antle & Wang, 2013) exploited these affordances (namely, as discussion props, for increased understanding of spatial relationships, and to offload mental processing onto physical actions) by integrating tangibles into spatial problems, thereby demonstrating the appropriateness of tangible EI for children's spatial learning, specifically in STEM-related topics (Abrahamson & Trninic, 2011). Another affordance of tangible EI that lends itself to the development of SS is the capacity to restructure the environmental elements through hands-on manipulation (Antle, 2009). Antle (2009) suggests that 'meaning is created through restructuring the spatial configuration of elements in the environment'. Children are therefore provided with spatial learning opportunities (e.g. proportional understanding (Abrahamson & Trninic, 2011), spatial thinking skills(Leduc-Mills & Eisenberg, 2011)) by manipulating the relationship between tangible expressions of the important components of target concepts.

Furthermore, EI provides children with the ability to experience spatial concepts from an egocentric representation (i.e. to view the object from their own vantage point). Previous work suggests that young children face greater difficulty (i.e. slower processing times, reduced accuracy) in processing allocentric, versus egocentric, spatial information (i.e. spatial memory) (Ruggiero *et al.*, 2016). By using EI, researchers can construct immersive learning scenarios (i.e. IDEs or VR) where children take on personas or act as elements of the concepts they are trying to master. In this way, children are exposed to spatial relationships, concepts and scenarios from a egocentric point of view, which might facilitate spatial understanding and knowledge acquisition. This was exemplified in Lindgren *et al.* (2016)'s MEteor project, where children used full-body movement to predict how gravitational forces influence an asteroid's behaviour as they moved throughout an immersive space simulation. By performing the asteroid's behaviour via body movement, children were given the opportunity to experience the asteroid's spatial relationships with its external environment from an internal perspective, which Lindgren *et al.* (2016) claim may cultivate 'conceptual anchors', which scaffold children's spatial learning experience. Additionally, Lindgren *et al.* (2016)'s study showed that by creating embodied metaphors, children experienced greater learning gains and increased learner motivation, when compared to a control group.

Research in EI and SS provides reason to believe that the capacities of EI may be particularly well suited for engaging SS. Although there is a growing body of empirical research, less work has been conducted on developing theoretical, albeit intermediate-level, knowledge in the embodied spatial domain, as well as corollary applications to STEM education. However, recent research signifies an embodied turn in the theory and practice (mainly through focused interventions) of STEM education (Abrahamson & Lindgren, 2014). Technology's essential role in supporting children's physical engagement with EI-based technologies allows researchers to make sense of how children think and interact with their bodies in ways that benefit their SS. This marriage offers powerful means of realizing the call for multidisciplinary research at the intersection of computer science, cognition and learning sciences. From our literature review, we identified how various EI capabilities have been utilized to support children's SS. However, in most cases, the research focuses on enhancing SS (Antle & Wang, 2013, Freina *et al.*, 2016, Leduc-Mills & Eisenberg, 2011, Lindgren *et al.*, 2016, Roberts *et al.*, 2014, Wang *et al.*, 2017, Zander *et al.*, 2016), and there are limited studies following a longitudinal research design and addressing aspects of SS development. The results of our review aligns with previous works that support the linkage between movement, action and comprehension (Kontra *et al.*, 2015) in relation to spatial cognition. This in turn supports our thesis that EI and SS may provide opportunities for STEM education and the benefits of incorporating physical movements into curricula. Ultimately, the identification of EI capabilities with specific SS, as determined in this work, takes an initial step towards improving spatial cognition that targets STEM education. Future empirical research should investigate design decisions by qualitatively observing phenomena related to how EI capacities support the various cognitive mechanisms, and focused quantitative or mixed-methods evaluations of those phenomena.

6.5. Limitations

Following the systematic methodology proposed by Kitchenham & Charters (2007) for performing a review of literature in a relatively narrow area ensures the quality of the outcome but also entails some limitations. First, one of the common limitations is the bias imposed by the search query, since keywords are discipline and language specific. We attempted to reduce this limitation by developing, applying and discussing the search terms between the authorship group until we reached consensus. Another common limitation is the bias induced from the selection of databases, journals and publications. To reduce this bias we considered a broad range of relevant venues, which included the main publishing venues related to HCI and learning technologies.

Further limitations include potential bias or inaccuracy in data extraction, as the authors of the selected studies do not necessarily use the same terminology and describe their studies at different levels of granularity. This induces bias in the interpretation of some findings, methods and approaches. To mitigate this, the authors read and discussed several papers numerous times until they agreed on the final coding. We coded each study with respect to the coding scheme presented in Table 4. However, different coding schemes may have shifted the focus of this review paper in other elements. Moreover, although different approaches, such as scoping review, narrative review, systematic mapping study or integrative review, might not have submerged as deeply into an area or be regarded as systematic, they offer other benefits that serve valuable purposes (e.g. creating a map of a wide research field). Despite the limitations of our methodological decisions, the selected method and implementation adhered to are well accepted and widely used in the area of CS (HCI in particular), providing certain assurance of the results.

Lastly, there has been a recent surge of interest in EI in HCI. However, this explosion has been paired with the emergence of a bewildering variety of terms such as 'embodied conduct', 'embodied cognition', 'whole-body interaction', 'tangible interaction', 'embodied conceptual metaphors', 'third-wave HCI' and 'somatics'. Issues attributed to a plethora of subtly different definitions are not unique to HCI researchers in cognitive science who, for example, have identified at least 12 different meanings of 'embodiment' (Rohrer, 2007).

6.6. Future Work

The current landscape reflects that researchers are diligently investigating how EI and SS function harmoniously, with a primary focus on EI as actor and SS as patient. With esteemed research emphasizing the importance of SS to academics and professions in STEM (Wai *et al.*, 2009), the growing support for EI as an engagement mechanism for SS (Chang *et al.*, 2017a,b, Clifton *et al.*, 2016, Keren *et al.*, 2012) and the increased emergence of technologies that activate the body, we predict a continued push towards the concurrent exploration of EI and SS.

The application of spatial problem-solving in a real-world scenario typically concerns ideation in 3D space, for example visualizing an object from a different vantage point, estimating the distance between yourself and an object in your surrounding environment or solving a Rubik's cube; however, the established instructional materials and test procedures currently employed to concentrate on SS are primarily exercised in 2D space, either on paper or on a computer screen (Chang *et al.*, 2017a). This reduced dimensionality of the problem space requires the learner to manage an additional layer of abstraction, and may in turn increase cognitive load. However, despite this potential negative consequence, only one study in our review addressed this issue. In their contribution to furthering spatial visualization skills, Leduc-Mills & Eisenberg (2011) presented UCube to investigate how children might overcome this '2D bottleneck' phenomenon, thereby bridging the conceptual/cognitive gap between 3D objects in physical space and their 2D on-screen representations. On the one hand, more dynamic EI-based tools may offer a new approach to SS development and assessment, by providing learners and test takers with a more realistic problem-solving scenario and enabling an arsenal of more expressive answering tactics to address the questions being asked. On the other hand, using an EI-based approach requires increased physical interaction that may fatigue participants, consequently reducing their ability to absorb or demonstrate knowledge accurately or effectively over prolonged amounts of time. Furthermore, in order for EI to be an effective means of SS development and assessment, the motor skills of the individuals involved should be established and differences offset to ensure fair evaluation, as observed by Wang *et al.* (2017). Although a handful of interventions engaged participants' movements in order to assess their spatial ability (Kitson *et al.*, 2015, Oulasvirta *et al.*, 2009), as discussed in section 5.5, none of the studies was explicitly designed to evaluate the efficacy of SS assessment by way of EI. We regard these directions of research to be worthy of future undertakings.

7. CONCLUSION

Recent decades have witnessed advances in both theoretical models of SS and EI technologies, yet critical questions remain unanswered regarding the interaction of the two topics, specifically concerning how the implementation of theoretical knowledge can guide future research and practice. EI has proven its capability of advancing transformative learning and research. The current review demonstrates the present landscape at the intersection between EI and SS. The authors analysed 36 peer-reviewed articles selected from the literature within the period 2008 and 2018.

This review aimed to explore the research advances at the intersection of EI and SS, paying particular attention to (RQ1) user groups and methodologies employed, (RQ2) how EI was realized through the union of technology and users' physical action, (RQ3) the distribution, purpose and evaluation of the selected SS and (RQ4) how EI was was employed to facilitate SS and the resulting implications for research and practice.

In conclusion, this paper presents insights from a SLR intersection between EI and SS over the past 10 years and makes the following contributions:

- identifies the aspects of EI and SS convergence that have been the focus of publications;
- summarizes the developments in research and practice with regard to EI and SS over the past 10 years;
- extrapolates implications from the findings and discusses how they may direct future research and practice, particularly concerning the design of EI mappings to enhance SS.

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7 APPENDIX

TABLE A1. Results from the coding process. Population: Ries et al. (2009) This study reports on combined results from old (2005) trails and new (2009) of an experiment previously conducted. It consists of 4 experiments. In experiment 0, participants were composed of 2005 trails participants aged 20–45, students from Dept of CS and Dept of Architecture and the 2009 current trail participants were passing by students. In experiments 1–3, participants consisted of persons recruited on campus, though no specified as students. Jetter et al. (2012) two separate experiments (20,16 participants) all university students. Kruijff et al. (2015) This study consisted of 4 experiments. Ex 1 & 2 had 15 participants (19–55 yr). Ex 3 & 4 had 16 participants (20–30). Zhang et al. (2016) This study consists of 2 experiments. I have reported only on the later. Kasahara et al. (2017) Reported only on the workshop study (not the preliminary study). Chang et al. (2017a) most were college students or recent grads (age 18–28).

Authors	Design	Method	Data Collection	Population Size	Technology & Category	Embodied Interaction	EI Scale	Spatial Skill	Spatial Skills Purpose	Pre/ Post	Research Objective
Abrahamson and Trninic (2011)	NE	QL	Interview Ob Video	K 22	C - Mathematical Imagery Trainer Screen that detects the coordinates of two balls that are held by the users	Child moves their hands to discover the proportion rules that control the colour on a screen	F	G	DG		RQ1) What are productive EI design principles? Given that computational environments enable designer to could literally any physical action with any sensory feedback, which specific couplings support the learning of particular targeted concepts? RQ2) What are the instructors roles in orchestrating learners development of perceptual motor skill and subsequent mathematical signification of this skill with symbolic apparati?
Antle and Wang (2013)	RM	MM	Questionnaire Ob Notes Ob Video	C 16	LTS - Tabletop C - Sensor augmented puzzle pieces	Multitouch gestures to solve puzzle	F	G	E		how tangibles and multitouch affect spatial task (puzzle) performance
Antle (2013)	TE	MM	Ob Video	K 132	LTS - Tabletop C - Sensor augmented puzzle pieces	Child used TUI (audio augmented puzzle pieces) in a collaborative puzzle solving task	F	G	E		as above
Boari and Fraser (2009)	QE	MM	Ob Unsp Interview	M 16	C - floor tiles with foot-fall detection, read wearable passive, RFID tags to direct users via LED com- posed arrows	Interaction with user sensitive floor tiles while navigating a maze	E	N	E		how the physicality of using Navitiles in a maze can support maze walkers spatial shortcut selection
Chang et al. (2017a)	TE	QT	Question-naires Pre SS Post SS	M 46	MT - Leap Motion VR - Occulus HMD (head tracking) C - sliding blocks with distance sensors	Hand tracking and tangibles during immersive problem solving involving spatial perspective	FV	O	DG	B: O	how engaging the motor system via tangible interaction in a virtual world increases embodiment and supports spatial skills

(Continued)

TABLE A1. Continued.

Authors	**Design**	**Method**	**Data Collection**	**Population Size**	**Technology & Category**	**Embodied Interaction**	**EI Scale**	**Spatial Skill**	**Spatial Skills Purpose**	**Pre/ Post**	**Research Objective**
Chang et al. (2017b)	NE	MM	Ob Video Ob Notes Questionnaire Interview CSI	C 10	MT - Leap Motion VR - Occulus HMD (head tracking) C - sliding blocks with distance sensors	Hand tracking and tangibles during immersive problem solving involving spatial perspective	FV	O	DS		as above
Chiu et al. (2018)	RM	MM	Motion Sensors Ob Unsp Questionnaire	K 15	MT - Leap motion DC - Computer	Gestural interface for shape construction game	F	MR, V	DG		how gestures can help engage and support children in spatial learning
Endert et al. (2011)	QE	MM	Other - Task Switching	C 24	C - GyroMouse enables Chair that sends mouse events to a standard mouse	Users (passive and active) chair rotation is used to control the computer mouse in the left/right direction.	F	N	E		The purpose of the study was the shed light on usability issues of embodied passive and active interaction techniques for spatial interaction on large. High-resolution displays.
Freina et al. (2016)	RM	QT	Questionnaire CSI Pre SS	K 87	VR - Occulus HMD	Varying levels of immersion while solving spatial perspective task	V	O	E	Pre: O	the effects of different levels of immersion on performance in spatial perspective task
Jrvinen et al. (2011)	QE	QT	Questionnaire Motion sensors Post SS	U 27	IDE - eXperience Induction Machine MT - sensors	Interaction mapping to walking or driving in VE	E	M, N	E	Post: M	how the different navigation modes (translation, rotation) affect the users experience, spatial memory, and sense of presence during navigation in a VE.
Jetter et al. (2012)	RM	QT	Logging	C* 36	T - Interactive tabletop, wireless mouse with trackball	Multitouch gestures to pan and zoom a map	F	M, N	E		how spatial indirectedness and various touch gestures (panning, zooming) spatial memory and navigation

(Continued)

TABLE A1. Continued.

Authors	Design	Method	Data Collection	Population Size	Technology & Category	Embodied Interaction	EI Scale	Spatial Skill	Spatial Skills Purpose	Pre/ Post	Research Objective
Kasahara et al. (2017)	NE	QL	Interview Ob Video Motion sensor	P* 12	MT - Optitrack motion capture VR - Occulus HMD (head tracking)	Exploratory movement in an IVE with HMD	VE	P	-		the effects of spatial- temporal deformation of a virtual avatar on self-perception
Keren et al. (2012)	NE	QT	Ob Video Ob Photo	K 9	C - Nao robot	Interaction with social assistive robot	FV	G	DG		how interactions with a social assistance robot encourages spatial thinking
Kim and Maher (2008)	RM	QT	Ob Video Ob Audio	C 7	LTS - Tabletop C - input blocks	Use of tracked 3D design blocks on a tabletop to solve a design task	F	V	E		H1) The use of TUIs can change designers 3D modelling actions in designing - 3D modelling actions may be dominated by epistemic actions. H2) The use of TUIs can change designers gesture actions in designing -more gesture actions may serve as complementary functions to 3D modelling actions in assisting in designers cognition. H3) the use of TUIs can change certain types of designers perceptual activities -designers may perceive more spatial relationships between elements, and create more and attend to new visuospatial features through the production of multiple representations. H4) The use of TUIs can change the design process -the changes in designers spatial cognition may increase problem-finding behaviours and the process of rerepresentation, which are associated with creative design

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TABLE A1. Continued.

Authors	Design	Method	Data Collection	Population Size	Technology & Category	Embodied Interaction	EI Scale	Spatial Skill	Spatial Skills Purpose	Pre/Post	Research Objective
Kim et al. (2010)	QE	MM	Questionnaire Ob Notes	C 48	IDE - CAVE H - iPhone MT - Intersense IS900 head tracker	FWIP on an iPhone or a Lemur, inside a CAVE	FE	N	E		to investigate the effects of the mapping of the humans embodied ability to the finger-based locomotion technique on spatial knowledge acquisition?
Kim et al. (2015)	QE	QT	Questionnaire Logging Pre SS	C 60	IDE - CAVE H - iPhone MT - Intersense IS900 head tracker	VR FWIP and full body walking navigation	FE	N	E	Pre: O Direction	how different navigation techniques (FWIP, WIP) support spatial learning
Kitson et al. (2015)	RM	MM	Interview Pointing tasks	C 30	IDE - projection C - motion cuing chair	Body swivel/tilt joystick- like interface on a navigation chair	E	N, O	E		the use of more embodied leaning chair interfaces facilitates spatial updating compared to traditional means
Kruijff et al. (2015)	RM	MM	Logging Ob Video Motion sensor Questionnaire	A* 31	VR MT - Occulus HMD (head tracking) C - Sony Dualshock 3 Gamepad C - backpack with inclination sensor	Static leaning and dynamic tilting while seated in VR	E	P, N, O	E		the effects of different leaning (tilt) on forward self-motion perception
Lakatos et al. (2014)	RM	QL	Ob Unsp	P 12	H - iPad MT - G-speak & retro-reflective tag glove	Spatially aware hand-held for user collaboration in 3D animation	F	P	E		the collaborative use of spatially aware tablet for 3D animation design
Larrue et al. (2014)	TE	MM	Ob Video Questionnaire Reconstitution tasks CSI Pre SS	C 80	IDE - Optoma/ ThemeScene Proj. MT - Optitrack C - modified treadmill & joystick	Varying degrees of rotation in VE navigation	E	N, M	DS	Pre: MR M, O	the effects of body-based information on transfer of spatial skills from virtual and real world

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TABLE A1. Continued.

Authors	Design	Method	Data Collection	Population Size	Technology & Category	Embodied Interaction	EI Scale	Spatial Skill	Spatial Skills Purpose	Pre/Post	Research Objective
Leduc-Mills and Eisen- berg (2011)	NE	QL	Ob Audio	HS	C - 4 x 4 grid with removable switch-enabled towers that maps 3D shape to computer	Child engages with the ON/OFF switches of the UCube towers to signify selecting a coordinate in space, corresponding to the vertex of a 3D geometric shape	F	G	E		The main purpose of the pilot study was to get an initial impression of how the Cube would act as an accessible 3D modelling took - how well it could help 3D novices overcame the 2D bottleneck
Lindgren et al. (2016)	TE	QT	Question-naire Pre/Post (NSS)	K 113	IDE MT - MEteor simulation	Child acted as a meteor and moves throughout dynamic project-ions that composed an outer space scenario. Child must enact the meteors trajectory paths when encountering gravitational forces of approaching asteroids, planets and space debris	E	G	E	Pre: Force Concept Inventory, Physics, attitude and science self-efficacy. Post: Force Concept Inventory, Physics, attitude and science self-efficacy	H1) Giving students the opportunity to enact planetary concepts with their bodies, and connecting them to representational supports (Graphs and other visualisations), will build student intuitions and facilitate subsequent reasoning about physical systems. H2) Embodied engagement will heighten feelings of agency and efficacy, leading to more positive attitudes about science and perceived values of the simulations experience.

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TABLE A1. Continued.

Authors	Design	Method	Data Collection	Population Size	Technology & Category	Embodied Interaction	EI Scale	Spatial Skill	Spatial Skills Purpose	Pre/Post	Research Objective
Marchal et al. (2011)	RM	MM	Question-naire Interview	A 16	VR - eMargin Z800 HMD C - Human joystick platform	Users leans in the direction that they would like to express walking in their VR scenario. The user s balance is what controls the locomotion.	E	N	E		1) Introduce a new original interface centred on the users balance to control their virtual locomotion in immersion tasks. (also introduce the new law that transformed the device orientation into locomotion velocities so that the Joy-man can be used with multiple varieties of IVE.) 2) aim to maintain a high level of immersion compared to handheld devices (such as joysticks)
Mazalek et al. (2011)	QE	QT	Logging Pre\Post SS	U 30	C - puppet suit interface	Wearing a puppet suit to control a virtual avatar to interact with teapots while experiencing a perspective shift	FV	MR	DG	B: MR	how a puppet interface and corresponding virtual avatar affect users mental rotation ability
Oulasvirta et al. (2009)	QE	MM	Logging Ob Audio Ob Video Pre(SS)	A 16	H - mobile	Bodily response to the dimension of a mobile map	E	P, N, M	E	Pre: MR, M	how the differences in the spatial qualities of a mobile map affect bodily engagement
Palleis and Hussmann (2016)	RM	QT	Question-naire CSI	M 18	LTS - Touchscreen	Varying degrees of on screen spatial indirectedness	F	M, N	E		the effects of spatial indirectedness in multi-touch panning UIs on spatial memory and navigation

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TABLE A1. Continued.

Authors	Design	Method	Data Collection	Population Size	Technology & Category	Embodied Interaction	EI Scale	Spatial Skill	Spatial Skills Purpose	Pre/Post	Research Objective
Peck et al. (2011)	TE	QT	Questionnaire Post(NSS)	A 36	VR - nVisor SX HMD MT - HiBall motion tracker	Redirected Free Walking with Distractors in VR	E	N	E	Post: Slater-Usoh-Steed Presence Questionnaire, Size prediction of VE	H: there is no difference between RFED, WIP and JS walking distances
Quarles et al. (2008)	QE	QT	Questionnaire Pre(SS) Pre/Post (NSS)	C 60	H - tablet with magic lens to augment interaction with an anesthia machine	Using a TUI (tablet with magic lens) to operate an anesthesia machine	F	G	E	Pre: Spatial skills (Figural - The Arrow Span Test, Vista - The Perspective Taking Ability Test, Environmental -Navigation of a virtual environment). Written test to determine how much learned in training. Post: visualise gas flow, Hands-on Test	H1) TUI users will have less difficulty than GUI and PUI users visualising the gas flow in the context of the real anethesia machine. H2) The ability of TUI users to visualise gas flow in the context of the real anaesthesia machine will be less dependent on spatial ability than for the GUI and PUIs. That is, TUI training will compensate for low spatial ability. H3) TUI users are able to understand abstract gas flow concepts, regardless of spatial ability. H4) The advantages provided by the TUI will be most directly associated with the intermediate, Vista-scale spatial ability. For the GUI and the PUI groups, then the vistsa scale spatial ability test will be the most strongly correlated ability to performance.

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TABLE A1. Continued.

Authors	Design	Method	Data Collection	Population Size	Technology & Category	Embodied Interaction	EI Scale	Spatial Skill	Spatial Skills Purpose	Pre/ Post	Research Objective
Ries et al. (2009)	RM	QT	Measure distances manually	M* 40	Ex0: VR - nVisorSX HMD MT - HiBall motion tracker system Ex 1-3: MT - Vicon + reflective markers	Varying levels of fidelity on a self-representing virtual avatar in VR	EV	P	E		how the varying levels of geometric and motion fidelity of a virtual avatar affect spatial perception (distance estimation)
Roberts et al. (2014)	NE	MM	Ob Video Ob Audio Questionnaire CSI	K 28	C - Wizard of Oz detection of clapping and foot movement	Stepping L/R or F/B to control timeline for data visualisation clapping hands to switch datasets	V	G	E		the effects of ego-moving embodiment on how people understand and relate to display of personalised data
Wang and Lindeman (2012)	RM	QT	Questionnaire Post(SS)	C 8	H - Bamboo tablet VR - eMargin Z800 HMD MT - SpacePoint Fusion sensor (head tracker) C - Wii Fit Balance Board on top of Reebok Core Board & TactaCage system	Leaning on a platform to navigate space	E	N, O	FE	Post O	When two difference stances on the comparing the flying surfboard interface (frontal and side- ways), the frontal stance will outscore the sideways stance in questionnaire ratings, spatial orientation tests, VE cognition tests, and performance on 3D VE travel tasks.
Wang et al. (2017)	QE	QT	Pre(SS\ NSS) CSI Post NSS	HS 211	H - iPad	App with multitouch and tilt	F	V, O	E	Pre: Physics, O, VMI, V Post: Physics	the effects of tilt enabled app on physics comprehension

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TABLE A1. Continued.

Authors	Design	Method	Data Collection	Population Size	Technology & Category	Embodied Interaction	EI Scale	Spatial Skill	Spatial Skills Purpose	Pre/Post	Research Objective
Wallet et al. (2009)	QE	QT	Other - Map score Pre/Post (SS)	C 90	IDE - projection & joystick	Sitting and either watching video walking through the pre-determined route, OR using a joystick to navigate self through the pre-determined route	E	N	DS	Pre: O, V, MR Test. Post: way finding, sketch mapping, picture classification	purpose: investigate the influence of the exploration mode of virtual environments (passive vs active) according to Route complexity (simple vs complex) on the quality of spatial knowledge transfer in three spatial tasks (way finding, sketch mapping, and picture classification) that require either egocentric, allocentric referential, or both.
Zaman et al. (2015)	NE	MM	Ob Audio Question-naire	C 10	VR - Occulus HMD MT - Leap Motion	Paired users share perspective in VR HMD while motion tracked hands arrange virtual furniture	F	P	E		the effects of a shared spatial immersion perspective on verbal communication between collaborators
Zander et al. (2016)	RM	MM	Ob Video Logging Question-naires	K 51	H - iPad	Touch gestures to interact with dynamic shapes on app	F	MR	E		how the effects of task performance, perceived mental effort, improved mental and temporal efficiency or a multitouch of mental rotation tasks
Zhang et al. (2016)	NE	QT	Motion Sensors (Kinect, glove Dance pad Balance board Micro-phone)	A* 15	MT - Kinect sensor, Data glove C - Microphone, Dance pad & Balance board	Problem solving using different interaction modalities	V	N	E		the effects of embodied interaction on levels of attention while solving a navigation task

TABLE A2. The different technologies belonging to each technology category, with their respective citations.

Technology Category	# Studies	Descriptions & Citation
Handhelds	9	iPhone (Kim et al., 2010) iPad (Wang et al., 2017; Zander et al., 2016; Kim et al., 2015; Lakatos et al., 2014) cell phone (Oulasvirta et al., 2009) tablet (Quarles et al., 2008; Roberts et al., 2014; Wang and Lindeman, 2012)
Large Touch Screens	5	tabletop (Antle and Wang, 2013; Antle, 2013; Jetter et al., 2012; Kim and Maher, 2008), large touch screen (Palleis and Hussmann, 2016)
Desktop Computer	1	desktop (Chiu et al., 2018)
Motion Tracking	16	Hiball tracking system (Peck et al., 2011), Vicon motion tracking system (Ries et al., 2009) sensors (Kim et al., 2015, 2010; Larrue et al., 2014) glove (Lakatos et al., 2014) Leap Motion (Chiu et al., 2018; Zaman et al., 2015; Chang et al., 2017a,b), XIM (Jrvinen et al., 2011) MEteor System (Lindgren et al., 2016) Microsoft Kinect (Zhang et al., 2016) Opitrack system (Kasahara et al., 2017) PhidgetSpatial inclination sensors (Kruijff et al., 2015), SpacePoint Fusion sensors (Wang and Lindeman, 2012)
Immersive Digital Environment	7	Cave System (Kim et al., 2015, 2010), screen/wall projection (Wallet et al., 2009; Kitson et al., 2015; Larrue et al., 2014) XIM (Jrvinen et al., 2011) MEteor System (Lindgren et al., 2016)
Virtual Reality	10	Occulus (Kasahara et al., 2017; Zaman et al., 2015; Chang et al., 2017a,b; Kruijff et al., 2015;Freina et al., 2016), nVisorSX (Ries et al., 2009; Peck et al., 2011), eMargin (Wang and Lindeman, 2012; Marchal et al., 2011)
Custom	18	motion cuing chair (Kitson et al., 2015), modified treadmill (Larrue et al., 2014), microphone dance pad Wii balance board (Zhang et al., 2016) sensor enabled sliding wooden block (Chang et al. 2017a,b), Sony Dualshock gamepad & joystick (Kruijff et al., 2015), Mathematical Imagery Trainer (Abrahamson and Trninic, 2011), Navitiles (floor tiles) (Boari and Fraser, 2009) Chairmouse (Endert et al., 2011), Robot (Keren et al., 2012) UCube (Leduc-Mills and Eisenberg, 2011), embodied puppet interface (Mazalek et al., 2011), RFID tags (Roberts et al., 2014), augmented puzzle (Antle and Wang, 2013; Antle, 2013), TactaCage (Wang and Lindeman, 2012), building blocks (Kim and Maher, 2008), human joystick platform (Marchal et al., 2011)

TABLE A3. Distribution of publications by embodiment intervention scale.

Scale	# Studies	Citation
Figural	14	(Quarles et al., 2008; Wang et al., 2017; Zander et al., 2016; Lakatos et al., 2014; Chiu et al., 2018; Zaman et al., 2015; Abrahamson and Trninic, 2011; Leduc-Mills and Eisenberg, 2011; Endert et al., 2011; Antle and Wang, 2013; Antle, 2013; Jetter et al., 2012; Palleis and Hussmann, 2016; Kim and Maher, 2008)
Vista	3	(Zhang et al., 2016; Roberts et al., 2014; Freina et al., 2016)
Environmental	11	(Oulasvirta et al., 2009; Wang and Lindeman, 2012; Wallet et al., 2009; Kitson et al., 2015; Jrvinen et al., 2011; Lindgren et al., 2016; Larrue et al., 2014; Kruijff et al., 2015; Boari and Fraser, 2009; Peck et al., 2011; Marchal et al., 2011)
Vista environmental	2	(Ries et al., 2009; Kasahara et al., 2017)
Figural environmental	2	(Kim et al., 2015, 2010)
Figural vista	4	(Keren et al., 2012; Mazalek et al., 2011; Chang et al., 2017a,b)

TABLE A4. Distribution of publications by spatial skill.

Spatial skill	# Studies	Citation
Navigation (N)	16	(Jrvinen et al., 2011; Jetter et al., 2012; Palleis and Hussmann, 2016; Oulasvirta et al., 2009; Boari and Fraser, 2009; Endert et al., 2011; Marchal et al., 2011; Peck et al., 2011; Zhang et al., 2016; Kim et al., 2015, 2010; Wallet et al., 2009; Larrue et al., 2014; Wang and Lindeman, 2012; Kitson et al., 2015; Kruijff et al., 2015)
Mental Rotation (MR)	3	(Mazalek et al., 2011; Zander et al., 2016; Chiu et al., 2018)
Spatial Perception (P)	6	(Oulasvirta et al., 2009; Kasahara et al., 2017; Lakatos et al., 2014; Ries et al., 2009; Zaman et al., 2015; Kruijff et al., 2015)
Spatial Orientation (O)	7	(Wang and Lindeman, 2012; Kitson et al., 2015; Kruijff et al., 2015; Chang et al., 2017a,b; Freina et al., 2016; Wang et al., 2017)
Spatial Memory (M)	5	(Jrvinen et al., 2011; Jetter et al., 2012; Palleis and Hussmann, 2016; Oulasvirta et al., 2009; Larrue et al., 2014)
Spatial Visualisation (V)	3	(Chiu et al., 2018; Kim and Maher, 2008; Wang et al., 2017)
General Spatial Skills (G)	8	(Antle and Wang, 2013; Roberts et al., 2014; Keren et al., 2012; Abrahamson and Trninic, 2011; Quarles et al., 2008; Leduc-Mills and Eisenberg, 2011; Lindgren et al., 2016; Antle, 2013)

TABLE A5. Distribution of publications by spatial skill purpose.

Spatial Skill Purpose (SSP)	# Studies	Citation
Development general (DG)	5	(Keren et al., 2012; Abrahamson and Trninic, 2011; Mazalek et al., 2011; Chiu et al., 2018; Chang et al., 2017a)
Development specialised (DS)	3	(Wallet et al., 2009; Larrue et al., 2014; Chang et al., 2017b)
Enhancement (E)	27	(Antle and Wang, 2013; Roberts et al., 2014; Quarles et al., 2008; Leduc-Mills and Eisenberg, 2011; Lindgren et al., 2016; Antle, 2013; Jrvinen et al., 2011; Jetter et al., 2012; Palleis and Hussmann, 2016; Oulasvirta et al., 2009; Zander et al., 2016; Boari and Fraser, 2009; Endert et al., 2011; Marchal et al., 2011; Peck et al., 2011; Zhang et al., 2016; Kim et al., 2015, 2010; Wang and Lindeman, 2012; Kitson et al., 2015; Lakatos et al., 2014; Ries et al., 2009; Zaman et al., 2015; Kruijff et al., 2015; Freina et al., 2016; Kim and Maher, 2008; Wang et al., 2017)
Not Classified	1	(Kasahara et al., 2017)

TABLE A6. Distribution of publications by research objective's thematics.

Research Objective Grouping	# Studies	Citation
Use of tangibles to enrich representation in problem solving	5	(Antle and Wang, 2013; Antle, 2013; Abrahamson and Trninic, 2011; Chang et al., 2017a,b; Lindgren et al., 2016)
Rotating/Leaning the body to facilitate navigation	10	(Endert et al., 2011; Jrvinen et al., 2011; Kim et al., 2015, 2010; Kitson et al., 2015; Kruijff, 2015; Larrue et al., 2014; Marchal et al., 2011; Wallet et al., 2009; Wang and Lindeman, 2012)
Teaching children spatial skills	9	(Abrahamson and Trninic, 2011; Antle, 2013; Chiu et al., 2018; Freina et al., 2016; Lindgren et al., 2016; Keren et al., 2012; Lindgren et al., 2016; Zander et al., 2016; Wang et al., 2017)
Tools for the work place	4	(Kim and Maher, 2008; Lakatos et al., 2014; Quarles et al., 2008; Zaman et al., 2015)
Involve avatars to understand and manipulate spatial concerns	3	(Kasahara et al., 2017; Mazalek et al., 2011; Ries et al., 2009)
Other	7	(Boari and Fraser, 2009; Jetter et al., 2012; Oulasvirta et al., 2009; Palleis and Hussmann, 2016; Peck et al., 2011; Roberts et al., 2014; Zhang et al., 2016)