Multisensory Perception and Learning: Linking Pedagogy, Psychophysics, and Human–Computer Interaction

Monica Gori[1],*, Sara Price[2], Fiona N. Newell[3], Nadia Berthouze[4] and Gualtiero Volpe[5]

1. U-VIP - Unit for Visually Impaired People, Fondazione Istituto Italiano di Tecnologia, Italy
2. Institute of Education, University College London, London, UK
3. Department of Psychology and Institute of Neuroscience, Trinity College Dublin, Dublin, Ireland
4. Interaction Centre. Div of Psychology & Lang Sciences, University College London, London, UK
5. InfoMus Lab, University of Genoa, Genoa, Italy

* To whom correspondence should be addressed. E-mail: monica.gori@iit.it
ORCID iDs: Price: 0000-0002-5092-1663; Newell: 0000-0002-7363-2346; Volpe: 0000-0003-0760-4627

Abstract

In this review, we discuss how specific sensory channels can mediate the learning of properties of the environment. In recent years, schools have increasingly been using multisensory technology for teaching. However, it still needs to be sufficiently grounded in neuroscientific and pedagogical evidence. Researchers have recently renewed understanding around the role of communication between sensory modalities during development. In the current review, we outline four principles that will aid technological development based on theoretical models of multisensory development and embodiment to foster in-depth, perceptual, and conceptual learning of mathematics. We also discuss how a multidisciplinary approach offers a unique contribution to development of new practical solutions for learning in school. Scientists, engineers, and pedagogical experts offer their interdisciplinary points of view on this topic. At the end of the review, we present our results, showing that one can use multiple sensory inputs and sensorimotor associations in multisensory technology to improve the discrimination of angles, but also possibly for educational purposes. Finally, we present an application, the 'RobotAngle' developed for primary (i.e., elementary) school children, which uses sounds and body movements to learn about angles.

1. Introduction

Teaching and learning technologies are increasingly present in classrooms, but children and teachers do not yet widely accept and use them. Although significant effort is invested in developing new digital environments for education, essential design and developmental considerations would improve their educational effectiveness. First, digital learning environments are typically predominantly visual and fail to exploit the other sensory modalities, such as audition and touch (including active touch or haptics), that are critical for perception and learning. When we speak about learning, we refer to the embodied cognition theory that does not separate perceptual and conceptual learning. The theory argues that conceptual understanding is grounded in perceptual experience and that perceptual and conceptual learning are inextricably intertwined. The implication of this is that "The richer the perceptual environment using multiple sensory modalities (e.g., using visuals, voiceovers, and movement) during initial learning, the better the student learning, understanding and motivation" (Segal *et al.*, 2014).

Recent research highlights the role of multisensory integration and how different sensory modalities influence children's learning. For example, the visual channel is not always the best sensory modality or the most effective channel to develop perceptual skills (Barrett & Newell, 2015; Gori *et al.*, 2008, 2010, 2012a, 2014a). Indeed, for some features, such as perceiving temporal properties, the auditory modality is the more accurate sense (McGovern *et al.*, 2017). This dominance is true for adults and children with and without disabilities (Gori *et al.*, 2012b, 2017). Similarly, the haptic modality seems crucial for processing size properties in the visual domain (Gori *et al.*, 2008, 2012c). Perception can therefore be influenced by the sensory modality best suited for the task, sometimes referred to as the modality-appropriateness hypothesis (Welch & Warren, 1980).

Second, most technological solutions are insufficiently grounded in educational practice. They do not adequately consider both the teachers' and students' needs and expectations, involve practitioners in the innovation and transformation process, or integrate into appropriate innovative pedagogical paradigms. Moreover, the technical design is typically not based on neuroscientific and pedagogical results. The current review speaks to these topics by bringing together an interdisciplinary team composed of pedagogical, educational, neuroscientific, and technological experts to present state of the art in research findings from across these disciplines. In particular,

the review builds upon previous work devoted to presenting the concept (Volpe & Gori, 2019) and methodology of our research (Price & Duffy, 2018) and extends it by identifying how this approach — grounded in neuroscientific and pedagogical evidence — provides a unique contribution to the development of new technological solutions for school learning. It mainly focuses on the authors' lab work, the studies carried out and the results obtained by applying the methodology that the project consortium proposed in the framework of the EU-H2020-ICT project 'weDRAW'. In the first part of the review, we discuss how the challenges in pedagogical practices and recent neuroscientific evidence may present novel opportunities for multisensory technology design and significant benefits to the learning process. In the second part of the review, we present the scientific results and technological development of the work activity of the authors through a single-use case for learning angles through sounds and body movements (these data are a summary of the data reported in Gori *et al.*, 2021).

2. Pedagogical Approach: the Role of Sensory Modalities and Multisensory Inputs in Learning

There has been a longstanding interest in how learning can be supported by using representations that engage multiple sensory modalities. For example, the Montessori education tradition uses artifacts like sandpaper letters that children trace with their fingers to develop the physical skill of learning to write. Papert (Papert, 1980) discussed the idea of body-syntonic reasoning in learning about geometry. This refers to students projecting an experiential understanding of how their own bodies move onto a representation of a turtle moving on a screen. In this case, turtle movements reflect those of the student: if the student moves forward, so too does the turtle. This approach, which has been extended using sensors to record and represent movement, seems to help children to experience and view graphs of their own movements over time to foster experiential knowledge of concepts such as rate of change (Ackermann, 2004). Indeed, recent advances in theories of embodied cognition highlight the important role of the sensory body, experience, emotion and social interaction for learning and development (e.g., Alibali & Nathan, 2012; Barsalou, 2008; Varela *et al.*, 1991). A central argument is that meaning and conceptual representation are grounded in perceptual and motor experience. In other words, *in situ* sensory experiences provide sensorimotor representations, or 'embodied tools' (through action, gesture and analogical

mapping) that one can use later in reasoning (Weisberg & Newcombe, 2017).

A substantial tranche of research, particularly in mathematics, shows the value of embodied and multisensory forms of interaction for learning. In mathematics, the body's role (embodied cognition) and proprioceptive feedback are backed by significant evidence in the literature (Abrahamson, 2011; Cress *et al.*, 2010). In particular, fostering 'mindful' movement supports mathematical problem solving (Ma, 2017; Rosenfeld, 2017; Shoval, 2011). For example, Shoval (2011) showed that children who were taught about angles through meaningful movements seemed to outperform those who a teacher taught verbally. The notion of 'meaningful' here refers to when bodily activities are related to a learning task in a conceptually meaningful way, such as swinging the forearm with the elbow fixed when learning about pendulum motion (Lindgren & Johnson-Glenberg, 2013). The authors argue that learners performing movements allowed them to encode concepts and externalise thoughts and understandings, cementing their learning. "In effect, one way of *knowing* a mathematical relationship is by *being* the relationship. In particular, learners can enact and therefore *become* mathematical relations by using *gestures*, an important type of body-based action" (Walkington *et al.*, 2014). Bautista *et al.* (2011) go as far as to state that interacting with mathematical principles 'in the flesh' and incorporating kinetic body movement might be required for children to develop abstract mathematical knowledge. Further evidence using a control group that separates motor activity from other modalities would be useful.

Another key area of evidence for embodied and multisensory forms of interaction derives from gesture studies. Goldin-Meadow and colleagues (2001) suggest that gestures can 'offload' some aspects of memory, augmenting working memory and thereby improving performance. Furthermore, research indicates that gestures simulate actions from mental representations of concepts and that those gestures are based on sensorimotor interaction. Results point to the notion of 'gestural congruency' (Segal *et al.*, 2014), where the child's action is linked to the underlying conceptual idea or representation (Lindgren & Johnson-Glenberg, 2013). Indeed, actions congruent with the nature of the underlying process of the task seem to improve performance and the likelihood of transferability of the skills in children (Schwarz & Martin, 2008). In addition, teacher gesture in the classroom may play an important role in conveying conceptual ideas to children (Alibali & Nathan, 2007). Representational gestures (those that convey aspects of their meaning, literally or metaphorically) demonstrate simulations of actions among mathematical objects (for instance conveying the slope on a graph), and metaphoric gestures demonstrate body-

based conceptual metaphors. For example, 'arithmetic is collecting objects'. Collectively, this work suggests that both using and observing congruent gestures seem beneficial for learning. The notion of conceptual metaphor draws on Lakoff and Johnson's (1980a, 1980b) work, which considers the role of sensorimotor experiences to be central in the foundation of human language and our conceptualisation of experienced phenomena (Hampe, 2005). Physical experiences form metaphorical analogies for abstract ideas. For example, the metaphor of 'love is a journey' is based on physical experience: similarly, one might say 'it's been a long road' or one has 'reached a cross-roads' as metaphors using physical experience to indicate social, professional, or emotional experiences that have nothing to do with actual roads.

An embodied perspective inherently embraces the idea of multimodal and multisensory learning, given its foundation in the body's sensory experience. Research in cognitive science has shown the different representational affordances of images, text, animation and changing digital interfaces for conveying ideas and concepts (e.g., Price, 2002; Stenning, 1998); "Diagrammatic representations also typically display information that is only implicit in sentential representations and that therefore has to be computed, sometime at great cost, to make it explicit for use" (Simon & Larkin, 1987, p. 65). Furthermore, research in social semiotics and the role of multimodal or multiple representations offer new ways of engaging with learning ideas (e.g., Ainsworth, 2006; Kress, 2009; Moreno & Mayer, 1999). For example, combining tangible and visual materials emphasizes mathematical principles and seems to promote reflection on the connection between these principles and the actions the students are performing (Cramer & Antle, 2015). In addition, haptic information about molecular forces in conjunction with a 3D visual protein model improves protein–ligand understanding (Bivall *et al.*, 2011). Finally, other theoretically grounded research exploring the cognitive impacts of multimodal learning materials (e.g., Moreno & Mayer, 1999) suggests that coherently integrating verbal and pictorial information to reduce the cognitive load for different processing channels (e.g., auditory and visual) may be pivotal.

Understanding how best to design and integrate multisensory approaches into education is complex. One limitation of studies in this area may be a lack of experimental designs that include control groups of children performing similar activities with different modalities and feedback. This might contribute to confirming the benefits provided by embodied and sensory stimulation. Neuroscientific research can inform this design through better understanding the development of sensory modalities across childhood and multisensory integration.

3. Neuroscientific Findings: Multisensory Integration and Sensory Interaction During Development

Researchers in many fields have considered the role of each of the sensory modalities on perception during child development. Such fields include developmental psychology, psychophysics, and neuroscience. This current research provides evidence for the importance of using multiple senses and how specific sensory modalities are fundamental to develop specific perceptual environmental properties. This highlights the value of understanding the role of the senses for different tasks at varying developmental stages to inform the design of new educational technology.

The same environmental features may be measured by more than one sensory system, so the brain must integrate redundant sensory information of a particular ecological property. For example, it can use the visual and haptic features of a grasped object (Ernst *et al.* 2007; Newell *et al.*, 2001; Woods *et al.*, 2008) or a spatial array (Newell *et al.*, 2005; Woods & Newell, 2004) into a coherent percept. Recent results show that individual sensory modalities communicate with each other to influence perception during the first years of life (see, e.g., Bremner *et al.*, 2012). Other findings show that in adults, multiple sensory inputs can benefit performance by improving multisensory precision compared to unisensory precision (Alais & Burr, 2004; Ernst *et al.*, 2007). Developmental studies investigating the emergence of this ability demonstrate that multisensory integration abilities are task-specific and develop at different ages for different tasks. For example, during the first years of primary (i.e., elementary) school, children begin integrating multisensory information for simple localization tasks (Rohlf *et al.*, 2020). For more complex tasks such as spatial bisection, vertical localization, navigation, size and orientation, multisensory integration develops after 8–10 years (Gori *et al.*, 2008, 2012b, 2012c; Nardini *et al.*, 2008, 2014; Petrini *et al.*, 2015). Researchers have also investigated how sensory information becomes calibrated against each other, such as how visual modality influences the development of audition or touch (Burr and Gori, 2012; Gori, 2015). Indeed, some have hypothesized that cross-modal calibration is an important developmental mechanism that occurs in some cases before the ability to integrate multisensory information occurs (Burr and Gori 2012; Gori 2015; Gori *et al.* 2008). This process is based on the idea that specific sensory modalities are more accurate (even if they are less precise)

during development and one uses them to 'train' the development of other sensory systems. Cross-modal calibration is important because, in a developing system, the sensory modalities and different body parts grow at different rates and multisensory integration may be less useful than having a reference sensory system that can help maintain sensory stability (Burr and Gori 2012; Gori 2015; Gori *et al.* 2008). For example, using the visual modality to calibrate haptic orientation perception might help create a more stable system for orientation (i.e., vision) that can be used as a reference by more variable haptic systems. The study of multisensory integration during typical development has offered results in support of cross-modal calibration (Gori *et al.* 2008, Cuturi *et al.*, 2018) and in the case of children with a disability (e.g., Cappagli *et al.* 2017; Gori *et al.* 2010; Tinelli *et al.* 2015). Cross-modal calibration during development for some tasks is task-specific. Indeed, some kind of cross-modal calibration occurs during the first period of life until the end of primary school and before multisensory integration development, i.e., orientation, size and space bisection perception (Gori *et al.*, 2008, 2012b, 2012c). In contrast, other forms of cross-modal calibration start later in life (after 8–10 years of age) after the beginning of multisensory integration abilities, such as audio-motor temporal recalibration and the localization of stimuli (Rohlf *et al.*, 2020; Vercillo *et al.*, 2015). For example, differing results that are typically observed between horizontal localization and horizontal bisection tasks might be related to stimulus complexity. For the localization task, the participants must localize a single stimulus source, and for the bisection task they must report the spatial position of the stimulus in the middle between two lateral stimuli (i.e., if closer to the first or to the second). In particular, the stimulus should be processed based on its relative metric for the bisection task, while for localization the estimation of the position in space requires less complex spatial calculations. For this reason, the role of visual calibration for the two mechanisms might differ.

Studies have also recently clarified the importance of specific sensory modalities for specific concepts' development. For example, children typically use haptic information to perceive the size of objects, whereas they use the visual system to understand their orientation (Cuturi & Gori, 2019; Gori *et al.*, 2008, 2012b, 2012c). Given the importance of sensory calibration during development, an object of study has been to investigate how the lack of one sensory modality affects the development of other sensory modalities. Results suggest that the absence of one sensory input can impact other modalities. For example, lack of vision affects the development of haptic orientation perception, while motor impairment affects visual size perception (Gori *et al.*,

2010, 2012a). These results suggest that sensory modalities play an essential role in how our brains learn specific environmental properties and the understanding of differences in multisensory and sensory abilities across typical and impaired children might help improve interventions for rehabilitation (Cappagli *et al.* 2017; Gori *et al.,* 2016) and education. Understanding how and when these perceptual skills develop during the primary (elementary) school years may provide fundamental knowledge for developing useful educational technology. For example, in the first years of primary school, combining audio and visual information presentation is often more suitable than presenting one signal alone (Rohlf *et al.*, 2020), especially for some tasks such as stimulus localization but not for others such as bisection (Gori *et al.*, 2012b).

As we discussed above, evidence for a supporting role of movement, particularly gestures, with regard to learning mathematical concepts has been reported. There is evidence that indicates motor representations play a major role in multisensory processing (Fogassi & Gallese, 2004) and motor planning can modulate multisensory integration in adults (Sober & Sabes, 2003). However, the role that action and action planning play for multisensory perception during development is still unclear. Psychologists and philosophers have long argued for the essential role of sensorimotor interaction with the world for cognitive development (Clark & Chalmers, 1998; Piaget, 1972; Vygotsky, 1978). For example, experts have recognized the fundamental role of external tools in shaping activity and mediating cognition (Luria, 1981; Vygotsky, 1978). Indeed, sensorimotor experience and interaction with the environment are fundamental to meaning-making and conceptual understanding, providing the basis for learning and playing an essential role in knowledge construction. One recent example is the demonstration of children's representation of number lines along different axes that Cooney *et al.* (2021) reported. In general, the study of sensory preferences for different tasks can improve technology for teaching specific concepts. For example, the haptic modality is important for size processing (e.g., Gori, Tinelli, Sandini, Cioni & Burr, 2012a), which enhances the importance of technological solutions that include haptic information in the teaching of size (e.g., by providing haptic feedback). Similarly, the audio modality is important for rhythm perception (Gori, Sandini & Burr, 2012b) and technology that can associate rhythm with mathematical concepts (e.g., fractions). These may also provide an alternative means of enhancing teaching and learning. In the next section, we present new technological solutions that one could use to develop educational technology, providing multisensory inputs.

Another essential feature is the potential to sense the child's affective state during the learning process and tailor multisensory feedback to the child's needs. As technology becomes a partner in the learning process, it is essential that it can sense children's related affective and cognitive states. While well designed multisensory feedback can foster confidence in the child, a child might also experience moments of frustration, confusion, and even boredom. It then becomes crucial that technology adapts to children's psychological needs. While negative affective states can be detrimental to learning if they remain unaddressed, positive conditions are also significant. A sign of excitement and curiosity may indicate that the child is ready to be challenged, while over-confidence may lead a child to overlook details (for a review, see Olugbade *et al.*, 2017). The affective computing field has shown that detecting emotional states from expressions is possible. We argue that in the current study's context, body expressions are particularly interesting because the body is engaged in exploring learning concepts and possibly expressing how the child feels about what is enacting through their body. For example, a child's arm may be hesitating while s/he extends them to form an angle. A growing body of work in psychology, neuroscience, and computing confirms body expression as a primary channel for understanding how a person feels (Kleinsmith & Bianchi-Berthouze, 2013) as powerful as facial expressions and even more in certain states. Aviezer *et al.* (2012) argue that body expressions are more informative than facial expressions for intense emotion. De Gelder (2009) also points out that body expressions provide information about how a person feels. They also inform about whether a person is ready to respond to the emotional state, such as whether a confused learner is prepared to invest more effort or is disengaging with the task.

4. Engineering Results: Multisensory Technology and Feedback, Affective State, and Flexibility

As we have argued, multisensory information and specific senses can be essential for developing environmental perception and learning. In this section, we discuss how recent technological development enables new ways of supporting multisensory learning. There are multisensory technologies at the base of this new approach (e.g., haptic, visual, and auditory interfaces) that can provide novel forms of multisensory interaction that can foster new ways of teaching and learning. Indeed, new technological solutions facilitate more bodily-based interaction compared with

desktop computing devices. Recent developments in computing extend opportunities to enhance sensorimotor interaction with learning experiences bringing research interest to understanding the interaction between mind, body, and digital tools: embodied interaction and embodied cognition. Multisensory technology can support concept exploration and understanding, and foster children's confidence in their capability to explore and learn concepts. Below we present three essential features of multisensory technology that can support inputting neuroscientific findings into new educational, technological solutions.

4.1. Multisensory Feedback

Contemporary work in human–computer interaction (HCI) within learning suggests ways in which whole-body and haptic interaction systems through multisensory feedback might support learning. Whole-body interactive technologies foster learning of abstract concepts (Antle *et al.*, 2013; Malinverni and Pares, 2014), combined with visual (e.g. Smith *et al.*, 2014) and aural augmentation (e.g. Bakker *et al.*, 2011). For example, Moving Sound (MoSo), a set of tangible artefacts that afford different kinds of movement (forwards, backwards, closer, further) mapped metaphorically onto the pitch, volume, and tempo of sounds, enabled children to explore and learn about the abstract qualities of sound (Bakker *et al.*, 2011). Indeed, Walkington and colleagues (2014) report greater transfer to novel problems when using full-body gestures/action.

More recently, haptic technologies have introduced new tactile experiences to learning. Through force and tactile feedback, haptic technologies enable simulated tactile sensations of an object's hardness, shape, and texture. Haptic augmented feedback is beneficial for recall, inference, and transfer in elementary learning contexts, particularly for learning about how gears work (Han & Black, 2011) and developing psychomotor skills (Zacharia & Michael, 2015). In the context of mathematics, haptics brings new sensory experiences on concepts being explored, including partial or unfamiliar perspectives of shapes (Davis *et al.*, 2017), and can foster children's dimensional deconstruction of shape in ways that underpin later enactive 3D shape communication (Price *et al.*, 2020). Research has explored haptic interaction systems among individuals with visual impairments, often focusing on supporting wayfinding, navigation and orientation using wearable haptic artefacts (e.g., He *et al.*, 2020; Kammoun *et al.*, 2012; Mattheiss *et al.*, 2017; Ross & Blasch, 2000). Other work has focused on designing interfaces to support the visually impaired

to engage with graphics through 3D tactile systems (e.g., Memeo *et al.*, 2021; Siu *et al.*, 2021) to support science (Han, 2020) and object recognition (Dhaher & Clements, 2017). Within the context of geometry, some initial work has explored means of engaging children with shape or topological configurations (e.g., Buzzi *et al.*, 2015), primarily using touch screens. However, few projects have explored their use in classroom-based environments.

Furthermore, the recent availability to the general public of cheap devices for virtual reality (VR) and augmented reality (AR) made these technologies suitable for large-scale employment in education. VR and AR are useful in sensorimotor stimulations where they are associated not only with visual and audio feedback but also with tactile stimulation (e.g., vibration on the hands) or interfaced with haptic robotic platforms (e.g., Omni or Phantom devices). These robotics devices can be used to support the drawing of virtual shapes or present haptic scenarios (e.g., virtual cartesian plane) that one can experience haptically through the definition of virtual forces and positional cues.

Although pioneering work (e.g., Kaufmann & Schmalstieg, 2003) dates to the early 2000s, research and applications of VR and AR for mathematical teaching have only recently become more widespread (for recent examples, see Salman *et al.*, 2019; Simonetti *et al.*, 2020; Stranger-Johannessen, 2018). These technologies would benefit from an interdisciplinary approach that identifies learning concepts the technologies can best convey and the perceptual mechanisms they can leverage.

One essential feature of multisensory technology for learning is the potential to provide sensory feedback associated with specific body movements or sensory interaction. Conceptual metaphors and interactional mappings between what computer designers call "input actions and output responses" provide a foundation for designing more intuitive sensorimotor interaction interfaces that foster meaningful action concerning learning concepts, such as (Lindgren & Johnson-Glenberg, 2013). In other words, grounding the interaction with technology (e.g., how input is provided, how feedback is conveyed, how feedback is produced for any given input, and so on) on metaphors of real life, i.e., utilizing mechanisms that somewhat mimic real life and support the development of more intuitive interfaces.

In digital experience design, Bakker and colleagues (Bakker *et al.*, 2012) drew on musical concepts such as tempo, volume, and pitch mapped to movement in terms of speed, proximity, and flow to design a series of physical interactive artifacts constraining movement in specific ways to

support children learning about abstract qualities of sound. Other work has focused on understanding how embodied interaction with the physical world can help in designing technologies to learn more abstract forms of knowledge. For example, Howison and colleagues (Howison *et al.*, 2011) investigated the role that bodily operations play in learning about proportional equivalence, showing that physical enaction of proportional equivalence supports one in developing understanding of this concept. Furthermore, Ma (2017) showed how the body supports communication and negotiation of geometrical mathematical ideas. However, few classroom technologies have moved beyond predominance of the visual modality (e.g., tablet applications for learning mathematics — see Note 1) to integrate information from multiple sensory modalities and foster congruent actions, in other words: meaningful actions concerning the concept being known (Segal *et al.*, 2014).

New technological solutions enable accurate and real-time mapping of motor behaviour onto multiple facets of sound, haptics, and visual media. In mathematics, sound and music content can be associated with arithmetic concepts. Mapping motor behaviour onto single dimensions of sound morphology (e.g., pitch, intensity, granularity, rhythm, and so on) can enable simple associations with arithmetic concepts (e.g., less/more, counting, summing, subtracting, etc.). The concept of order (i.e., less/more) is conveyable by associating a motor feature (kinetic energy or posture expansion are some examples) with sound granularity. Thus, as the child moves more (or the more the child expands their body), the sound content becomes richer and denser. The concept of fractions can be associated with the musical pulse of a percussive sound so that smaller fractions relate to faster (i.e., shorter in time) pulses, as happens in music in which a half note has a duration that is twice as long as that of a quarter note. In more traditional approaches (e.g., making sounds with objects or musical instruments), a precise mapping of motor features onto sound and music features would be impossible, since acting upon a sound source would simultaneously affect many audio parameters. However, current technology can support the mapping of motor behaviour onto multiple sound morphology dimensions. Technology can also enable one to map different movement features onto varying features of sound morphology (e.g., energy onto intensity, expansion onto granularity, fluidity onto rhythm, and so on).

4.2. Affective State

Advances have been made in the computational field to automatically classify the emotional states of a person from their body. The recent but fast-growing body of work for this affective state is due to the current availability of low-cost, full-body sensing technology and its availability in an everyday context (e.g., Kinect, wearable devices). Bianchi-Berthouze and colleagues (Bianchi-Berthouze, 2003) and Camurri and colleagues (Camurri *et al.*, 2003) have pioneered this field by showing the possibility of capturing dimensional (valence, arousal, control, and avoidance) and certain facets of emotional states. By investigating these expressions in naturalistic settings, they have also shown that the automatic recognition of realistic body expressions reaches performances similar to those observed for automatic identification of facial expressions (Aung *et al.*, 2015; Griffin *et al.*, 2015). Body expressions are an informative affective channel in intelligent tutoring systems (Cooper *et al.*, 2011; D'Mello & Graesser, 2010). These studies show that many learning-related affective states (e.g., boredom, confidence, confusion, engagement, excitement, flow, frustration) are detectable using this modality. Work has also been done to examine children (Sanghvi *et al.*, 2011) engaged in in-game activities showing reliable performances. However, technology for detecting affect in education is being considered in only very controlled situations, mainly seated, and where the body is not explicitly engaged as a source of multisensory experience within the specified learning tasks.

4.3. Enabling Teachers

Another essential feature is the potential for multisensory technological flexibility in allowing teachers to configure the learning experiences. Teachers can choose, for example, which motor features are mapped onto which sound parameters, supporting a child to quickly achieve fine-grained control on the sound parameters. This requires many years of practice, such as with a traditional musical instrument. One can easily re-adapt this approach exploited for musical aspects for education technology design, allowing for effective exploitation of an embodied and enactive pedagogical approach. This can foster effectiveness by using the best modality for each specific concept to teach, improve personalization and flexibility for teachers and students in the learning process, and be easily re-adapted for children with impairments.

Because of the properties discussed above, we argue herein that multisensory interfaces can support engagement with learning concepts in active and participative ways, encouraging

exploration, discovery, and experimentation through manipulation and tactile feedback as well as visual and aural representations. These experiential modes have potential to bridge the gap between concrete and abstract understanding, where one can exploit features of different sensory modalities to foster interpretation and meaning-making. For example, the auditory modality might be better for understanding rhythm than the visual modality, and the former might be linked to some mathematical concepts that are proximate to musical concepts, like fractions. Considering these aspects, multisensory technologies are ideal for effectively supporting a pedagogical approach that exploits specific sensory modalities to teach different concepts, as suggested by neuroscientific findings (e.g., the possibility of developing new technological methods that associate audio rhythm with visual fractions to facilitate the comprehension of this concept).

4.4. Considerations About Multisensory Technological Solutions

Current digital technologies used in the classroom commonly rely on the visual modality for conveying learning concepts. For example, there are multiple applications for tablets for learning mathematics (Note 2), all relying on 'seeing' digital content rather than physically interacting with mathematical ideas. While theories of embodied cognition commonly underpin more contemporary design and development of digital learning environments that better exploit sensorimotor and multisensory interaction, it is not theoretically grounded on psychophysical or neuroscientific research findings. In the following section, we discuss key challenges and considerations in designing and developing technology for education.

4.4.1. The First Consideration Is that Technological Development Should Be More Child- and Teacher-Centred

Although a common goal for developing educational technology in general, here it assumes a particular relevance. It means that the designer can assess (i) the effective sensory modality for the child to learn a specific concept and (ii) whether specific impairments require exploiting sensory modalities. For example, recent studies showed that one could use musical training as a therapeutic tool for treating children with dyslexia (Overy, 2003; Overy *et al.*, 2003). In our view, the teacher plays a central part as a *mediator* in employing technology. This means that an iterative methodology of design, development, and evaluation through a framework of a participatory

design involving both teachers and students must consider usability, pedagogical effectiveness and customisability. As a mediator of learning, teachers need customizable options that enable them to choose modalities and features related to their teaching concept. Following an initial evaluation phase, we may then identify the best modalities linked to different concepts, personalize the technology to exploit the selected sensory modality, and evaluate learning process outcomes. As a side issue, technology that measures affective state may also help with screening for behavioural problems and addressing them.

4.4.2. The Second Consideration Is that a More Embodied and Enactive Pedagogical Approach Should Be Used to Develop New Technological Solutions

With this approach, teachers can use different sensorimotor feedback (audio, haptic, proprioception and visual) to teach new concepts to primary-school children. Such an approach would be more direct, natural and intuitive since it is based on the experience itself and perceptual responses to motor acts. Moreover, using movement and sensorimotor interaction for learning deepens and strengthens education and retention (Shoval, 2011), and multisensory designs to foster new engagement with mathematical ideas (Ma, 2017; Price *et al.*, 2020a, 2020b; Yiannoutsou êt al., 2018). For example, previous studies suggest that body movement enhances spatial perception across visual and haptic modalities (Pasqualotto *et al.*, 2005). Moreover, both space perception and spatial awareness are improvable through the association of body movement and sounds (Cappagli *et al.*, 2017; Cuppone *et al.*, 2018; Finocchietti *et al.*, 2015a, 2015b). A more active role of the user might also improve the engagement of the child in the task.

4.4.3. The Third Consideration Is that Multiple Sensory Feedback and Inputs Should Be Considered in New Applications

Multisensory technologies can overcome the major challenge of the consolidated hegemony of vision in current educational practice. Focusing too much on one single sensory channel may represent a severe issue for the effectiveness and personalization of the learning process and the inclusion of children with impairments (such as visual impairment) or indeed children who benefit from alternative routes into learning. If we consider multisensory platforms (e.g., systems that provide audio and visual information simultaneously) we can break through these barriers because both visually impaired and sighted children can use the same system to learn based on different

sensory signals. Concerning *effectiveness*, this may be impacted by inappropriate, incorrect, or excessive vision usage, which is not always the most effective modality for communicating certain concepts to children since different modalities communicate different information. As for *personalization*, a pedagogical methodology based almost exclusively on the visual modality would not consider the learning potential and routes of access for learning in children, exploiting the different modalities in ways that more comprehensively convey different kinds of information (i.e., the haptic modality is often better for the perception of texture than vision). Every child could use a different learning approach mediated by the most effective sensory signal for the specific person (e.g., for learning shape, one child would prefer to use the visual signal and another the haptic signal). In the example above, visually impaired but also typical children can use the audio modality or both visual and auditory simultaneously based on their own individual predisposition.

4.4.4. The Fourth Consideration Is that New Technological Solutions Should Be Grounded on Pedagogical and Neuroscientific Needs

Multisensory technology should provide effective means to teach specific concepts that would benefit from digital augmentation or mediation from a pedagogical perspective. These could be particularly difficult concepts for children to understand or where sensory modalities other than vision can enhance critical ideas. In a recent survey we conducted with teachers (see Cuturi *et al.*, 2021a), we observed that the challenging concepts depend on school level. We observed that, in primary-school-aged children, in geometrical context, concepts related to mental transformations are problematic while angles are medium and high difficulty for students at levels 3–4 (8–10 years old). Moreover, teachers showed that other sensory modalities (such as haptic) can benefit the understanding of 'isometric transformations': tipping, translation, and rotation. All this information may offer guidance toward improving teaching strategies and technology design. According to scientific evidence, from a neuroscientific perspective, multisensory technology should leverage the sensorial, perceptual, and cognitive capabilities that children possess. A technology capable of detecting specific motor behaviours in a target population (e.g., primary school) of children makes sense only if scientific evidence shows that children in in that population can display such actions. The same holds for feedback: multisensory technology can provide specific feedback (e.g., based on the auditory pitch). This approach is right if (i) children can perceive it (e.g., they developed the perception of tone), and (ii) an association exists or a new

association is trained between the feedback and the concept to be communicated (e.g., the association between pitch and size of objects or audio and body movements as in the ABBI device — Gori *et al.*, 2017).

In the second part of this review, we use this approach to address critical points in an example of an application we discuss. To that end, we investigated the sensory preferences of children for sound and visual angles. We then studied the pedagogical and affective ability of the child to learn angles through sounds. Finally, we describe a new flexible technology that we developed to understand angles through body movements and sounds as feedback. We expect that utilizing movements (e.g., gestures) that are conceptually congruent with the knowledge being learned increases the child's performance, learning, understanding and motivation (Segal *et al.*, 2014). In the context of this new technological approach, called the 'RobotAngle', children make concept-congruent movements with their bodies that correspond with changes in perceptually enhanced, using both vision and audition. Moreover, these sensory motor associations improve space representation and facilitate the link between the body and space (as shown in the ABBI device —Cappagli *et al.* 2017; Cuppone *et al.*, 2018; Finocchietti *et al.* 2015a).

4.4.5. One Example of Our Approach: the Use of Sounds and Body Movements to Learn Angles
We have considered the issues outlined above in designing and developing a new digital environment to support children's learning of angles using the association between audition and body movement. This effort was conducted as part of our collaborative project, 'weDRAW'. In the next paragraph, we present our results and the interdisciplinary process of work we adopted from a pedagogical, psychophysical, and HCI point of view.

4.4.6. Pedagogical Inputs
From a pedagogical point of view, we first needed to better understand the role of the body in children's experience of mathematical ideas (e.g., shapes and angles in geometry). We use this to inform a digital game design that effectively fosters meaningful bodily enactment for young children (aged 6–11) learning of geometric concepts. It was necessary for us to understand how to encourage meaningful or congruent action and design useful reflective feedback, such as designing appropriate feedback that augments bodily interaction to support practical mathematical thinking. Accordingly, we collected data on childrens' spontaneous, intuitive body actions and bodily

representation for engaging with and creating angles and shapes to understand how whole-body sensory experiences can engage children in meaning-making around ideas of shape and angles (Price & Duffy, 2018). This study engaged 29 students from 7 to 11 years of age to examine the kinds of bodily movements children make and how they interpret and use them to experience different angles and shapes. Doing so informs the benefits and limitations of bodily exploration. This allows us to inform the design of augmented sensory interaction to support effective mathematical thinking. Drawing on Henderson and Taimiða (2005), activities were purposefully designed to ensure a clear maths concept was explored, where the whole-body movement was integral to the task. The study aligned activities with the school curriculum in the UK (also consistent with pedagogical goals in other educational systems across Europe). It defined angles as a geometric figure (a pair of rays with a common endpoint), a dynamic figure (a turn or rotation), and a measure (Price & Duffy, 2018). Children worked in groups of 3 or 4 with three tasks: (i) to use their bodies to make angles; (ii) use their bodies to make shapes; and (iii) use their bodies to create symmetry of shapes.

Facilitators encouraged the children to think aloud as they worked, using questions such as "what is the new angle?", "is it bigger or smaller than the first angle?" and "what is the combined angle in total?" The study collected video data for qualitative data analysis to examine moment-by-moment bodily interactions through a focus on gesture, action, facial expression, body posture, and talk (Jewitt, 2015). The aim of the research was to inform how one can use the body to enact and engage with mathematical ideas. Research showed that it is necessary to account for several considerations when using the body as a learning resource. Fundamental bodily limitations became more apparent as children used various bodily postures to represent different angles and communicate them to others (Fig. 1A). For example, stretching beyond acute angles to create obtuse or reflex angles was physically challenging.

Differences in children's physical bodies (e.g., the lengths of their arms or legs) led to differences in collaborative shape formation (e.g., two intended equilateral sides were different lengths) and potential misconceptions of properties of regular polygons. Figure 1B presents a group standing in a circle to form a triangle with joined arms. Getting the right length was a challenge due to differences in participants' arm lengths. This challenge enabled opportunities for reflection about their aim, the discrepancy between that and their body make-up, and their exploring ways to achieve appropriate lengths, such as overlapping their arms or 'shortening' their

arms. This result provides evidence that the children were thinking about the critical features of equilateral triangles.

Finally, differences in how children perceived or 'felt' the positioning of their bodies in space compared to how this looked to others suggest the need to foster better awareness of the body in space and make the links between 'felt' and 'overt' bodily experience explicit.

4.5. Psychophysical Inputs

Starting from these pedagogical results, from a psychophysical point of view, we investigated how alternative sensory modalities could be associated with angle processing. To achieve this goal, we investigated the phenomenon of perceptual correspondence during development (Cuturi *et al.*, 2019, 2021b). Developmental studies show that children can associate visual size with non-visual stimuli that are apparently unrelated, such as pure-tone frequencies or proprioception (Holmes *et al.*, in prep.). So far, most literature has focused on audiovisual size associations by showing that children can associate low pure-tone frequencies with big objects and high pure-tone frequencies with small ones. We investigated whether the sound frequency could offer information about angle size. Toward this goal, we investigated how cross-modal audiovisual associations develop during primary-school age, from 6 to 11 years old (Cuturi *et al.*, 2019). To unveil such patterns, we took advantage of a range of pure auditory tones and tested how primary-school children match sounds with visually presented shapes. We tested 66 children (6–11 years old) in an audiovisual matching task involving a range of pure-tone frequencies. Visual stimuli were angles of different sizes (see Fig. 2A).

Our study asked participants to indicate the shape matching the sound they heard. We present the results in Fig. 2B. All children associated large angles with low-pitch and small angles with high-pitch sounds. Interestingly, older children made greater use of intermediate visual sizes than younger children to provide their responses. Audiovisual associations for finer stimuli might develop later, likely depending on the maturation of supramodal size perception processes. Upon consideration of this result, we suggest that these natural audiovisual size correspondences are useable for educational purposes by supporting the learning of relative size, including angles. Moreover, the effectiveness of such correspondences is optimisable according to children's specific developmental stages.

4.6. Inputs from Affective Technology: the Engineering Approach

It is crucial to consider the user state in the role of technology. To investigate this point, we also studied children's affective state in using sounds and body movements to learn angles with technology. Olugbade and colleagues (Olugbade *et al.*, 2020) present a system that automatically infers a child's affective and cognitive states as they are engaged in mathematical games by exploring mathematical concepts through their body and sound feedback. In recent work (Volta *et al.*, 2019) we extend this approach to children with visual impairment. While these works are preliminary, they show the potential new multi-sensing and affect-aware technology offers to learn during uncontrolled naturalistic settings. Their research also offers an in-depth analysis of how children express certain affective and cognitive states related to learning through their body and other modalities. We considered three categories of features in the movement analysis: low-level features (e.g., velocity, energy, postural configurations), spatial/temporal features (e.g., trajectory length, distance covered), and motion descriptors (directness, smoothness, impulsivity). These types of features have been effective in affect detection (De Silva and Bianchi-Berthouze, 2004; Griffin *et al.*, 2015). Furthermore, they are related to features that experts have used to assess self-efficacy, curiosity, and reflectivity in other contexts (Olugbade *et al.*, 2018). Studies also indicate that postural configurations capture various states across contexts and cultures (Kleinsmith *et al.*, 2005). Additionally, using more advanced machine-learning techniques, we let the algorithms identify patterns of movement that relate to such states and possibly better capture differences due to learning tasks and children's idiosyncrasies.

5. New Technological Solution Based on Previous Inputs: the Engineering Approach

Starting from the results in the previous sections, we developed a new technological solution that enables real-time association of visual and auditory feedback with body movements and angle processing. We considered the pedagogical inputs of providing students with a means of exploring the concept of angles by involving full-body movement discussed in the previous pedagogical section. We focused on angles because angles were among the most challenging concepts revealed by the survey conducted with teachers (for more details see Cuturi *et al.*, 2021a). Teachers had to

indicate the mathematical concepts that they perceived as difficult to teach with the visual modality and which alternative inputs (audio or touch) could effectively teach a particular concept (when the visual modality is missing, such as in the case of visually impaired individuals). The results we obtained suggest that angles are particularly difficult for children to understand. Indeed, angle comprehension presented at medium and high difficulty levels for students in the age group of 8–10 years old (in-class years specific to their national educational system). This result is supported by scientific evidence showing that the angle concept is probably difficult to learn because angle size is difficult to disentangle from overall figure size, which is in agreement with other work (Dillon & Spelke, 2018; Gibson & Maurer, 2016; Mitchelmore & White, 2000). We implemented the results obtained through the psychophysical tests by employing specific auditory pitches to infer angle size. Finally, we included the analysis of the three features of movement highlighted in the abovementioned affective study. As a result, we developed a full-body activity where different proprioceptive skills and sensory modalities need to solve a mathematical problem concerning angles.

The activity we developed can be potentially used both in the classroom and at home, and its setup consists of a range-imaging sensor device (in particular, we used Kinect v.2), connected to a personal computer. The software was implemented in the EyesWeb XMI platform (Volpe *et al.*, 2016) and Unity. In this process, a major difficulty consisted of designing a clear relation between the geometrical concept and the child's embodied experience to create a strong relation that was useful for learning. We addressed this challenge by involving teachers, pedagogues, and psychologists in the design process and conducting early testing of the produced prototypes with children. We applied a user-centred, game-based, non-invasive, and ecological approach using simple and natural stimuli to adapt training language to the subject, rather than forcing the opposite process. We ran workshops during the technological development wherein children engaged with the designs while the teachers evaluated the results. This iterative interactive approach between all users and the adaptation of the technology based on user feedback and experience allowed us to fine-tune the methods. Throughout this process, an important relation emerged between sound and body movement and was highlighted by our psychophysical experiments (e.g., the sound pitch should be associated with dimension of the angle aperture)

After a short introduction explaining the rules at the beginning of the activity, the system asks the child to move their arms in the space to represent a specific angle. The system tracks the

child's movements to compute which angle is defined. Once the child can reproduce the required angle correctly, the system proposed a new angle. The goal consists of reconstructing all the angles contained in a complex shape (e.g., the house represented in Fig. 3). To facilitate the child's adjustment of their movements, the study provided two kinds of feedback: (i) visual feedback (i.e., two lines drawing the angle created by the arms) and (ii) auditory feedback (i.e., a different sound for each angle). A sound model maps each angle to a different sound. Starting from a reference sound (associated to 0°), the sound pitch is modified (i.e., pitch decreases) until the angle size changes (i.e., the angle size increases).

From a technological point of view, the study used the Kinect sensor to acquire the 3D coordinates of the head and the child's hands. This data is used to control in real-time the production of the visual and auditory feedback. The study uses EyesWeb XMI and Unity for such purposes. Features of the activity (e.g., the auditory and visual content feedback) are adaptable to each child. For example, we developed a version for visually impaired children by adapting the visual feedback with higher contrast to allow them to perform the same activity as sighted children. During the activity, we stored movement data to perform movement and affective analysis to assess the child's behaviour, performance, and progression.

Twenty-four children of 7 ($n = 12$) and 9 ($n = 12$) years old used the application. We divided children into two groups: one trained with the RobotAngle activity ($n = 12$) and the other trained with another audio-motor activity unrelated to angle but on fractions ($n = 12$). Both groups underwent pre- and post-evaluation tests before and after five activity sessions. This experiment is extensively described in Gori *et al.* (2021). Their study briefly describes the paradigm and methods, and partially presents the results (see Gori *et al.*, 2021, for more details). In the first session, they performed the first part of the pre-test finished in the second session. In the second part of the second session and in the third session they performed the training, as well as in the first part of the fourth session. In the second part or the fourth session and in the fifth session, the researchers tested children in the post-tests (same duration and structure of the activity for both groups, see Gori *et al.*, 2021, for more details). The pre- and post-evaluation sessions were composed of three tests that investigate proportional reasoning, numerosity and general geometrical knowledge. In our study, we performed a measure of number estimation, a measure of proportional reasoning and a measure of visuo-spatial abilities.

In the number estimation test, we required participants to localize the position of a specific number (e.g., 17) on a bold horizontal number line from 0 to 100 (or from −100 to 0) in each trial. For the proportional-reasoning measure, we used the previously developed Proportional Reasoning Task (Boyer *et al.* 2008). We asked participants to select a proportion that matched a target juice mixture, determining proportionality by the relative quantities of juice and water parts. For the measure of visuo-spatial abilities, we used a validated Italian battery of tests specifically developed to link visuo-spatial abilities with geometrical knowledge (Mammarella *et al.*, 2012). Results suggest that children of different ages improved in different tasks after different training. For example, the only test children improved upon after training with the RobotAngle was the visuospatial abilities test. The improvement was specific to children of 9 years and not of 7 years, suggesting that the effect of the training is age-specific and perhaps associated with developmental knowledge. Contrarily, the 7-years-old children improved their performance in the number line task with both training activities (i.e., RobotAngle and BodyFraction). A possible explanation of this result is that younger children might benefit more from associating numbers, arm aperture and sound. Both training activities provided this association: in the RobotAngle activity, the relationship was created between numbers and increased quantities represented as angle apertures corresponding to sound and arm apertures. In the BodyFraction activity, children created the relationship in the correspondence between increasing/decreasing numbers arm/legs aperture/rhythm. Thus, 7-years-old children less familiar with the concept of numbers along a continuum might benefit more from training. In contrast, for the geometrical test, the RobotAngle activity is more directly related to geometry and may therefore be useful at 9 years of age but too complex for younger children to internalize well. This result suggests that there might be a relationship between the school level and learning stage of the selected groups of children, indicating that training effects might differ based on age. There is a need for age appropriateness for specific task–modality combinations to ensure the usefulness of sensorimotor training. We can speculate that the benefit can be maximal considering the window between the need of improving the understanding of the concept and cognitive basis to learn it. Seven-years-old children improve more in the number line and 9-years-old children in the geometrical test because these tests present complex, relatively unfamiliar concepts for their age. Moreover, children should already have the foundation necessary to learn the concepts through the training. Indeed, geometrical concepts for

7-years-old children are too complex to learn, and even with the aid of the training they do not reach this ability. The same is not true for the 9-years-old children.

The findings suggest that informative sounds associated with body movements can be a powerful tool for improving some perceptual concepts related to mathematics learning (see Gori *et al.* for more details). Admittedly, a limitation of this work is that we were unable to compare the benefit the technology provides with standard teaching methods that only have visual aids (e.g., classroom-taught lesson with angles drawn on a blackboard). In future work, it will be essential to include a control group who learn angles with the standard teaching approach.

In this context, future must evaluate, possibly with longitudinal studies, whether these enhancements and the sensorimotor association are maintained after the training ends and the generality of learning for other sensory information. Moreover, future experiments should be performed to clarify how much improvement is a result of the sensorimotor experience compared to the visual and/or auditory experience. To support a wider usage of the application among students, we developed a new optimized version of the game to distribute in schools. It is endowed with an interactive whiteboard (IWB) already in place in most classrooms without using a Kinect and a PC. The activity includes the first part of the multisensory exploration of angles and the second part of training related to the angles' understanding using body movements. It is freely available online (see this link for more details: https://s3a.deascuola.it/wedraw/WEDRAW.html; this link is permanent, and the activity is in Italian).

6. Conclusion

Drawing on recent advances in the literature, we argue for the beneficial use of different sensorimotor signals such as audition, haptics, vision, and movement to teach primary-school children mathematical concepts in novel ways. This review has presented a new approach that links pedagogics with neuroscience and engineering to develop new technology for learning mathematical concepts at primary (i.e., elementary) schools. We discussed the limitations of existing technological solutions and proposed key points that stand to improve learning activities. As a result of this interdisciplinary approach, we presented a new platform based on audiovisual and body movement to teach geometrical concepts of angles to children. In future work, it will be crucial to identify a quantitative method to better measure the improvement that standard

procedures and new technological training engenders. To conclude, we propose that multisensory technology offers essential inputs to develop new applications and technology for learning and that a central, multidisciplinary approach will allow the field to reach this critical goal.

Notes

1. http://www.pcadvisor.co.uk/feature/software/best-maths-apps-for-children-3380559/
2. http://www.pcadvisor.co.uk/feature/software/best-maths-apps-for-children-3380559/

References

Abrahamson, D. and Trninic, D. (2011). Toward an embodied-interaction design framework for mathematical concepts. IDC '11: Proceedings of the 10th International Conference on Interaction Design and Children, pp. 1–10. doi: 10.1145/1999030.1999031

Ackermann, E. K. (2004). Constructing knowledge and transforming the world, in: *A Learning Zone of One's Own: Sharing Representations and Flow in Collaborative Learning Environments*, M. Tokoro and L. Steels (Eds), pp. 15–37. IOS Press, Amsterdam, Netherlands.

Ainsworth, S. (2006). DeFT: A conceptual framework for considering learning with multiple representations, *Learn. Instruct.* **16**, 183–198. https://doi.org/10.1016/j.learninstruc.2006.03.001

Alais, D. and Burr, D. (2004). The ventriloquist effect results from near-optimal bimodal integration, *Curr. Biol.* **14**, 257–262. doi: 10.1016/j.cub.2004.01.029

Alibali, M.W. & Nathan, M.J. (2007). Teachers' gestures as a means of scaffolding students' understanding: evidence from an early algebra lesson, in: *Video Research in the Learning Sciences*, R. Goldman, R. Pea, B. Barron and S. J. Derry (Eds), pp. 349–365. Erlbaum, Mahwah, NJ, USA.

Alibali, M. W. & Nathan, M. J. (2012). Embodiment in mathematics teaching and learning: evidence from learners' and teachers' gestures, *J. Learn. Sci.* **21**, 247–286. https://doi.org/10.1080/10508406.2011.611446

Antle, A. N., Corness, G. and Bevans, A. (2013). Balancing justice: comparing whole body and controller-based interaction for an abstract domain, *Int. J. Arts Technol.* **6**, 388–409.

Aung, M. S. H., Kaltwang, S., Romera-Paredes, B., Martinez, B., Singh, A., Cella, M., Valstar, M., Meng, H., Kemp, A., Shafizadeh, M. and Elkins, A. C. (2015). The automatic detection of chronic pain-related expression: requirements,

challenges and the multimodal EmoPain dataset, *IEEE Trans. Affect. Comput.* **7**, 435–451. doi: 10.1109/TAFFC.2015.2462830

Aviezer, H., Trope, Y. and Todorov, A. (2012). Body cues, not facial expressions, discriminate between intense positive and negative emotions, *Science* **338**, 1225–1229. doi: 10.1126/science.1224313

Bakker, S., van den Hoven, E. and Antle, A. N. (2011). MoSo tangibles: evaluating embodied learning, in: *TEI '11: Proceedings of the fifth international conference on Tangible, embedded, and embodied interaction*, pp. 85–92. https://doi.org/10.1145/1935701.1935720

Bakker, S., Antle, A. N. and van den Hoven, E. (2012). Embodied metaphors in tangible interaction design, *Pers. Ubiquitous Comput.* **16**, 433–449. https://doi.org/10.1007/s00779-011-0410-4

Barrett, M. M. and Newell, F. N. (2015). Task-specific, age related effects in the cross-modal identification and localisation of objects, *Multisens. Res.* **28**, 111–151. doi: 10.1163/22134808-00002479

Barsalou, L.W. (2008). Grounded cognition, *Annu. Rev. Psychol.* **49**, 617–645. https://doi.org/10.1146/annurev.psych.59.103006.093639

Bautista, R. E. D., Gonzales, W. and Jain, D. (2011). Factors associated with poor seizure control and increased side effects after switching to generic antiepileptic drugs, *Epilepsy Res.* **95**, 158–167. doi: 10.1016/j.eplepsyres.2011.03.014

Bevilacqua, F., Boyer, E. O., Françoise, J., Houix, O., Susini, P., Roby-Brami, A. and Hanneton, S. (2016). Sensori-motor learning with movement sonification: perspectives from recent interdisciplinary studies, *Front Neurosci.* **10**, 385. doi: 10.3389/fnins.2016.00385

Bianchi-Berthouze, N. (2003). K-DIME: an affective image filtering system, *IEEE MultiMedia* **10**, 103–106. doi: 10.1109/MMUL.2003.1218262

Bivall, P., Ainsworth, S. and Tibell, L. A. E. (2011). Do haptic representations help complex molecular learning? *Sci. Educ.* **95**, 700–719. https://doi.org/10.1002/sce.20439

Boyer, T. W., Levine, S. C. and Huttenlocher, J. (2008). Development of proportional reasoning: Where young children go wrong, *Dev. Psychol.* **44**, 1478–1490. https://doi.org/10.1037/a0013110

Burr, D. and Gori, M. (2012). Multisensory integration develops late in humans, in: *Neural Bases of Multisensory Processes*, M. M. Murray and M. T. Wallace (Eds), ch. 18. CRC Press/Taylor & Francis, Boca Raton, FL, USA.

Buzzi, M.C., Buzzi, M., Leporini, B., Senette, C. (2015) Playing with geometry: a multimodal android app for blind children, in: *CHItaly 2015: Proceedings of the 11th Biannual Conference on Italian SIGCHI, Rome, Italy*, pp. 134–137. https://doi.org/10.1145/2808435.2808458

Camurri, A., Lagerlöf, I. and Volpe, G. (2003). Recognizing emotion from dance movement: comparison of spectator recognition and automated techniques, *Int. J. Hum. Comput. Stud.* **59**, 213–225. https://doi.org/10.1016/S1071-5819(03)00050-8

Cappagli, G. and Gori, M. (2016). Auditory spatial localization: Developmental delay in children with visual impairments, *Res. Dev. Disabil.* **53**, 391–398. https://doi.org/10.1016/j.ridd.2016.02.019

Cappagli, G., Finocchietti, S., Baud-Bovy, G., Cocchi, E. and Gori, M. (2017). Multisensory rehabilitation training improves spatial perception in totally but not partially visually deprived children, *Front. Integr. Neurosci.* **11**, 29. doi: 10.3389/fnint.2017.00029

Clark, A. and Chalmers, D. (1998). The extended mind, *Analysis* **58**, 7–19.

Cooney, S. M., Holmes, C. A. and Newell, F. N. (2021). Children's spatial–numerical associations on horizontal, vertical, and sagittal axes*, J. Exp. Child Psychol.* **209**, 105169. https://doi.org/10.1016/j.jecp.2021.105169

Cooper, D. G., Arroyo, I. and Woolf, B. P. (2011). Actionable affective processing for automatic tutor interventions, in: *New Perspectives on Affect and Learning Technologies*, R. Calvo and S. D'Mello (Eds), pp. 127–140. Springer, New York, NY, USA. https://doi.org/10.1007/978-1-4419-9625-1_10

Cramer, E.S. & Antle, A.N. (2015) Button matrix: how tangible interfaces can structure physical experiences for learning, in: *TEI '15: Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction*, pp. 301–304. doi: 10.1145/2677199.2680566

Cress, U., Fischer, U., Moeller, K., Sauter, C. and Nuerk, H. C. (2010). The use of a digital dance mat for training kindergarten children in a magnitude comparison task. Learning in the Disciplines, in: *ICLS '10: Proceedings of the 9th International Conference of the Learning Sciences*, Vol. 1, pp. 105–112. doi: 10.5555/1854360.1854374

Cuppone, A. V., Cappagli, G. and Gori, M. (2018). Audio feedback associated with body movement enhances audio and somatosensory spatial representation, *Front. Integr. Neurosci.* **12**, 37. doi: 10.3389/fnint.2018.00037

Cuturi, L. F. and Gori, M. (2019). Biases in the visual and haptic subjective vertical reveal the role of proprioceptive/vestibular priors in child development, *Front, Neurol.* **9**, 1151. doi: 10.3389/fneur.2018.01151

Cuturi, L. F., Tonelli, A., Cappagli, G. and Gori, M. (2019). Coarse to fine audio-visual size correspondences develop during primary school age, *Front. Psychol.* 10, 2068. doi: 10.3389/fpsyg.2019.02068

Cuturi, L. F., Cappagli, G., Yiannoutsou, N., Price, S. and Gori, M. (2021a). Informing the design of a multisensory learning environment for elementary mathematics learning, *J. Multimod. User Interfaces* **2021**, 1–17. https://doi.org/10.1007/s12193-021-00382-y

Cuturi, L. F., Cappagli, G., Tonelli, A., Cocchi, E. and Gori, M. (2021b). Perceiving size through sound in sighted and visually impaired children*, Cogn. Dev.* **60**, 101125. https://doi.org/10.1016/j.cogdev.2021.101125

Davis, R.L., Martinez, M. O., Schneider, O, MacLean, K. E., Okamura, A. M. and Blikstein, P. (2017). The haptic bridge: Towards a theory for haptic-supported learning, in: *IDC '17: Proceedings of the 2017 Conference on Interaction Design and Children*, pp. 51–60. https://doi.org/10.1145/3078072.3079755

De Gelder, B. (2009). Why bodies? Twelve reasons for including bodily expressions in affective neuroscience*, Philos. Trans. R. Soc. Lond. B Biol. Sci.* **364**, 3475–3484. https://doi.org/10.1098/rstb.2009.0190

De Silva, P. R. and Bianchi-Berthouze, N. (2004). Modeling human affective postures:an information theoretic characterization of posture features*, Comput. Animat. Virtual Worlds* **15**, 269–276. doi: 10.5555/1071157.1071172

Dhaher, Y. and Clements, R. (2017). A virtual haptic platform to assist seeing impaired learning: proof of concept*. J. Blind. Innov. Res.* **7**.

Dillon, M. R. and Spelke, E. S. (2018). From map reading to geometric intuitions*, Dev. Psychol.* **54**, 1304–1316. https://doi.org/10.1037/dev0000509

D'Mello, S. and Graesser, A. C. (2010). Mining bodily patterns of affective experience during learning, in: *Educational Data Mining 2010. 3rd International Conference on Educational Data Mining*, pp. 31–40.

Ernst, M. O., Lange, C. and Newell, F. N. (2007). Multisensory recognition of actively explored objects, *Can. J. Exp. Psychol.* **61**, 242–253. https://doi.org/10.1037/cjep2007025

Finocchietti, S., Cappagli, G., Porquis, L. B., Baud-Bovy, G., Cocchi, E. and Gori, M. (2015a). Evaluation of the Audio Bracelet for Blind Interaction for improving mobility and spatial cognition in early blind children - A pilot study. 37th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC), pp. 7998–8001. doi: 10.1109/EMBC.2015.7320248

Finocchietti, S., Cappagli, G. and Gori, M. (2015b). Encoding audio motion: spatial impairment in early blind individuals, *Front. Psychol.* **6**, 1357. doi: 10.3389/fpsyg.2015.01357

Fogassi, L. and Gallese, V. (2004). Action as a binding key to multisensory integration, in: *The Handbook of Multisensory Processes*, G. A. Calvert, C. Spence and B. E. Stein (Eds), pp. 425–441. MIT Press, Cambridge, MA, USA.

Gibson, L. C. and Maurer, D. (2016). Development of SNARC and distance effects and their relation to mathematical and visuospatial abilities, *J. Exp. Child Psychol.* **150**, 301–313. https://doi.org/10.1016/j.jecp.2016.05.009

Goldin-Meadow, S., Nusbaum, H., Kelly, S.D. and Wagner, S. (2001). Explaining math: gesturing lightens the load. *Psychol. Sci.* 1**2**, 516–522. https://doi.org/10.1111/1467-9280.00395

Gori, M. (2015). Multisensory integration and calibration in children and adults with and without sensory and motor disabilities, *Multisens Res.* **28**, 71–99. doi:10.1163/22134808-00002478

Gori, M., Del Viva, M., Sandini, G. and Burr, D. (2008). Young children do not integrate visual and haptic form information, *Curr. Biol.* **18**, 694–698. doi: 10.1016/j.cub.2008.04.036

Gori, M., Sandini, G., Martinoli, C. and Burr, D. (2010). Poor haptic orientation discrimination in nonsighted children may reflect disruption of cross-sensory calibration, *Curr. Biol.* **20**, 223–225. doi: 10.1016/j.cub.2009.11.069

Gori, M., Tinelli, F., Sandini, G., Cioni, G. and Burr, D. (2012a). Impaired visual size-discrimination in children with movement disorders, *Neuropsychologia* **50**, 1838–1843. doi: 10.1016/j.neuropsychologia.2012.04.009

Gori, M., Sandini, G. and Burr, D. (2012b). Development of visuo-auditory integration in space and time, *Front. Integr. Neurosci.* **6**, 77. doi: 10.3389/fnint.2012.00077

Gori, M., Giuliana, L., Sandini, G. and Burr, D. (2012c). Visual size perception and haptic calibration during development, *Dev. Sci.* **15**, 854–862. doi: 10.1111/j.1467-7687.2012.2012.01183.x

Gori, M., Squeri, V., Sciutti, A., Masia, L., Sandini, G. and Konczak, J. (2012). Motor commands in children interfere with their haptic perception of objects, *Exp. Brain Res.* **223**, 149–157. doi: 10.1007/s00221-012-3248-8

Gori, M., Sandini, G., Martinoli, C. and Burr, D. C. (2014a). Impairment of auditory spatial localization in congenitally blind human subjects, *Brain* **137**, 288–293. doi: 10.1093/brain/awt311

Gori, M., Vercillo, T., Sandini, G. and Burr, D. (2014). Tactile feedback improves auditory spatial localization, *Front. Psychol.* **5**, 1121. doi: 10.3389/fpsyg.2014.01121

Gori, M., Chilosi, A., Forli, F. and Burr, D. (2017). Audio-visual temporal perception in children with restored hearing, *Neuropsychologia* **99**, 350–359. doi: 10.1016/j.neuropsychologia.2017.03.025

Gori, M., Volpe, G., Cappagli, G., Volta, E. and Cuturi, L. F. (2021). Embodied multisensory training for learning in primary school children, in: *2021 IEEE International Conference on Development and Learning (ICDL),* pp. 1–7. doi: 10.1109/ICDL49984.2021.9515596

Griffin, H., Aung, M. H., Romera-Paredes, B., McLoughlin, C., McKeown, G., Curran, W. and Bianchi-Berthouze, N. (2015). Perception and automatic recognition of laughter from whole-body motion: continuous and categorical perspectives, *IEEE Trans. Affect. Comput.* **6**, 165–178. doi: 10.1109/TAFFC.2015.2390627

Hampe, B. (2005). Image schemas in cognitive linguistics: Introduction, in: *From Perception to Meaning: Image Schemas in Cognitive Linguistics*, Beate Hampe (Ed.), pp. 1–12. Mouton de Gruyter, Berlin, Germany.

Han, R., (2020) Masters thesis for Master of Design in Inclusive Design Toronto, Ontario, Canada, 2020.

Han, I. and Black, J. B. (2011), in:corporating haptic feedback in simulation for learning physics, *Comput. Educ.* **57**, 2281–2290. https://doi.org/10.1016/j.compedu.2011.06.012

Henderson, D. and Taimiða, D. (2005). *Experiencing Geometry. Euclidean and Non-Euclidean with History*. Cornell University, New York, NY, USA.

Holmes, C. Cooney, SM. Dempsey, P. and Newell, F.N. (in prep.). Visuo-proprioceptive perception of geometric angles across development. Manuscript in preparation.

Howison, M., Trninic, D., Reinholz, D. and Abrahamson, D. (2011). The Mathematical Imagery Trainer: from embodied interaction to conceptual learning, in: *CHI '11:Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pp. 1989–1998. https://doi.org/10.1145/1978942.1979230

Jewitt, C. (2015). *Researching the Digital: A Multimodal Approach.* Routledge, London, UK.

Kammoun, S., Jouffrais, C., Guerreiro, T., Nicolau H. and Jorge. J., (2012) Guiding blind people with haptic feedback, in: *Pervasive 2012 Workshop on Frontiers in Accessibility for Pervasive Computing*, Newcastle, UK, proceedings, pp. 217–226.

Kaufmann, H. & Schmalstieg, D. (2003). Mathematics and geometry education with collaborative augmented reality, *Comput. Graph.* **27**, 339–345, doi: 10.1016/S0097-8493(03)00028-1

Kleinsmith, A. and Bianchi-Berthouze, N. (2013). Affective body expression perception and recognition: A survey, *IEEE Trans. Affect. Comput.* **4**, 15–33. doi: 10.1109/T-AFFC.2012.16

Kleinsmith, A., De Silva, R. and Berthouze, N. (2005). Recognizing emotion from postures: cross-cultural differences in user modeling, in: L. Ardissono, P. Brna and A. Mitrovic (Eds), *UM 2005: User Modeling 2005*. Lecture Notes in Computer Science, Vol. 3538. Springer, Berlin, Germany. https://doi.org/10.1007/11527886_8

Kress, G. (2009) *Multimodality: A Social Semiotic Approach to Contemporary Communication*. Routledge, London, UK. https://doi.org/10.4324/9780203970034

Lakoff, G. & Johnson, M. (1980a). *Metaphors we Live by*. University of Chicago Press, Chicago, IL, USA.

Lakoff, G. & Johnson, M. (1980b). The metaphorical structure of the human conceptual system, *Cogn. Sci.* **4**, 195–208. https://doi.org/10.1207/s15516709cog0402_4

Lindgren, R. and Johnson-Glenberg, M. (2013). Emboldened by embodiment: six precepts for research on embodied learning and mixed reality, *Educ. Res.* **42**, 445–452. https://doi.org/10.3102/0013189X13511661

Luria, A. R. (1981). *Language and Cognition*. J. V. Wertsch, Ed. Wiley Interscience, New York, NY, USA.

Ma, J. Y. (2017). Multi-party, whole-body interactions in mathematical activity, *Cogn. Instruct.* **35**, 141–164. https://doi.org/10.1080/07370008.2017.1282485

Malinverni, L. and Pares, N. (2014). Learning of abstract concepts through full-body interaction: a systematic review, *Educ. Technol. Soc.* **17**, 100–116.

Mammarella, I. C., Todeschini, M., Englaro, G., Lucangeli, D. and Cornoldi C. (2012). *Geometriatest. Prove di Valutazione per la Scuola Primaria e Secondaria di Primo Grado*. Edizioni Erickson, Trento, Italy.

Manches, A. and O'Malley, C. (2012). Tangibles for learning: a representational analysis of physical manipulation, *Pers. Ubiquitous Comput.* **16**, 405–419. https://doi.org/10.1007/s00779-011-0406-0

Marshall, P. (2007). Do tangible interfaces enhance learning? in: *TEI '07 Proceedings of the 1st international conference on Tangible and embedded interaction*, pp. 163–170. https://doi.org/10.1145/1226969.1227004

Mattheiss, E., Regal, G., Sellitsch, D. and Tscheligi, M. (2017). User-centred design with visually impaired pupils: A case study of a game editor for orientation and mobility training, *Int. J. Child Comput. Interact.* **11**, 12–18. https://doi.org/10.1016/j.ijcci.2016.11.001

McGovern, D. P., Walsh, K. S., Bell, J. and Newell, F. N. (2017). Individual differences in context-dependent effects reveal common mechanisms underlying the direction aftereffect and direction repulsion,. *Vision Res.* **141**, 109–116. doi: 10.1016/j.visres.2016.08.009

Memeo, M., Jacono, M., Sandini, G. & Brayda, L. (2021). Enabling visually impaired people to learn three-dimensional tactile graphics with a 3DOF haptic mouse, *J. Neuroeng. Rehabil.* **18**, 146. https://doi.org/10.1186/s12984-021-00935-y

Mitchelmore, M. C. and White, P. (2000). Development of angle concepts by progressive abstraction and generalisation, *Educ. Stud. Math.* **41**, 209–238. https://doi.org/10.1023/A:1003927811079

Moreno, R. and Mayer, R. E. (1999). Cognitive principles of multimedia learning: The role of modality and contiguity, *J. Educ. Psychol.* **91**, 358–368. https://doi.org/10.1037/0022-0663.91.2.358

Nardini, M., Jones, P., Bedford, R. and Braddick, O. (2008). Development of cue integration in human navigation, *Curr. Biol.* **18**, 689–693. doi: 10.1016/j.cub.2008.04.021

Nardini, M., Dekker, T. and Petrini, K. (2014). Crossmodal integration: a glimpse into the development of sensory remapping, *Curr. Biol.* **24**, R532–534. doi: 10.1016/j.cub.2014.04.034

Newell, F. N., Ernst, M. O., Tjan, B. S. and Bülthoff, H. H. (2001). Viewpoint dependence in visual and haptic object recognition, *Psychol. Sci.* **12**, 37–42. https://doi.org/10.1111/1467-9280.00307

Newell, F. N., Woods, A. T., Mernagh, M. and Bülthoff, H. H. (2005). Visual, haptic and crossmodal recognition of scenes, *Exp. Brain Res.* **161**, 233–242. https://doi.org/10.1007/s00221-004-2067-y

Olugbade, T., Cuturi, L., Cappagli, G., Volta, E., Alborno, P., Newbold, J., Bianchi-Berthouze, N., Baud-Bovy, G. and Gori, M. (2017). What cognitive and affective states should technology monitor to support learning? in: *MIE 2017: Proceedings of the 1st ACM SIGCHI International Workshop on Multimodal Interaction for Education*, pp. 22–25. doi: 10.1145/3139513.3139522

Olugbade, T. A., Bianchi-Berthouze, N., Marquardt, N. and Williams, A. C. de C. (2018). Human observer and automatic assessment of movement related self-efficacy in chronic pain: from exercise to functional activity, *IEEE Trans. Affect. Comput.* **11**, 214–229. doi: 10.1109/TAFFC.2018.2798576

Olugbade, T., Newbold, J., Johnson, R., Volta, E., Alborno, P., Niewiadomski, R., Dillon, M., Volpe, G. and Bianchi-Berthouze, N. (2020). Automatic detection of reflective thinking in mathematical problem solving based on unconstrained bodily exploration, *IEEE Trans. Affect. Comput.* doi: 10.1109/TAFFC.2020.2978069

Overy, K. (2003). Dyslexia and music — from timing deficits to musical intervention, *Ann. N. Y. Acad. Sci.* **999**, 497–505. https://doi.org/10.1196/annals.1284.060

Overy, K., Nicolson, R. I., Fawcett, A. J. and Clarke, E. F. (2003). Dyslexia and music: measuring musical timing skills, *Dyslexia* **9**, 18–36. doi: 10.1002/dys.233

Papert, S. (1980). *Mindstorms: Children, Computers, and Powerful Ideas*. Basic Books, Inc., New York, NY, USA

Pasqualotto, A., Finucane, C. M. and Newell, F. N. (2005). Visual and haptic representations of scenes are updated with observer movement, *Exp. Brain Res.* **166**, 481–488. https://doi.org/10.1007/s00221-005-2388-5

Petrini, K., Jones, P. R., Smith, L. and Nardini, M. (2015). Hearing where the eyes see: children use an irrelevant visual cue when localizing sounds, *Child Dev.* **86**, 1449–1457. doi: 10.1111/cdev.12397

Piaget, J. (1972). Intellectual evolution from adolescence to adulthood, *Hum. Dev.* **15**, 1–12. https://doi.org/10.1159/000271225

Price, S. (2002) Animated diagrams: How effective are explicit dynamics for learners? in: *Keeping Learning Complex: The Proceedings of the Fifth International Conference of the Learning Sciences (ICLS)*, P. Bell, R. Stevens and T. Satwitz (Eds), pp. 344–351. Erlbaum, Mahwah, NJ, USA.

Price, S. (2013). Tangibles: technologies and interaction for learning, in: *The SAGE Handbook of Digital Technology Research*, S. Price, C. Jewitt and B. Brown (Eds), pp. 307–325. SAGE, Los Angeles, CA, USA.

Price, S. and Duffy, S. (2018). Opportunities and challenges of bodily interaction for geometry learning to inform technology design, *Multimodal Technol. Interact.* **2**, 41. doi: 10.3390/mti2030041

Price, S. and Jewitt, C. (2013). A multimodal approach to examining 'embodiment' in tangible learning environments, in: *TEI '13: Proceedings of 7th International Conference on Tangible, Embedded and Embodied Interaction*, pp. 43–50. https://doi.org/10.1145/2460625.2460632

Price, S., Yiannoutsou, N., Johnson, R. and Outhwaite, L. (2020a). Enacting elementary geometry: Participatory 'haptic' sense-making, *Dig. Exper. Math. Educ.* **7**, 22–47. doi: 10.1007/s40751-020-00079-z

Price, S., Yiannoutsou, N. and Vezzoli, Y. (2020b). Making the body tangible: Elementary geometry learning through VR, *Dig. Exper. Math. Educ.* **6**, 213–232. doi: 10.1007/s40751-020-00071-7

Rohlf, S., Li, L., Bruns, P. and Roder, B. (2020). Multisensory integration develops prior to crossmodal recalibration, *Curr. Biol.* **30**, 1726–1732 doi: 10.1016/j.cub.2020.02.048

Rosenfeld, M. (2017). *Math on the Move: Engaging Students in Whole Body Learning*. Heinemann, Portsmouth, NH, USA.

Ross, D.A. and Blasch, B.B., (2000). Wearable interfaces for orientation and wayfinding, in: *Assets '00: Proceedings of the Fourth International ACM Conference on Assistive Technologies*, pp. 193–200. https://doi.org/10.1145/354324.354380

Salman, E., Besevli, C., Göksun, T., Özcan, O. and Urey, H. (2019). Exploring projection based mixed reality with tangibles for nonsymbolic preschool math education, in: *TEI '19: Proceedings of the Thirteenth International Conference on Tangible, Embedded, and Embodied Interaction*, pp. 205–212. doi 10.1145/3294109.3300981

Sanghvi, J., Castellano, G., Leite, I., Pereira, A., McOwan, P. W. and Paiva, A. (2011). Automatic analysis of affective postures and body motion to detect engagement with a game companion, in: *HRI '11: Proceedings of the 6th International Conference on Human–Robot Interaction*, pp. 305–312. https://doi.org/10.1145/1957656.1957781

Sciutti, A., Squeri, V., Gori, M., Masia, L., Sandini, G. and Konczak, J. (2010). Predicted sensory feedback derived from motor commands does not improve haptic sensitivity, *Exp. Brain Res.* **200**, 259–267. doi: 10.1007/s00221-009-1996-x

Schwartz, D.L. and Martin, T. (2008). Distributed learning and mutual adaptation, *Pragmat. Cogn.* **14**, 313–332. doi:10.1075/pc.14.2.11sch

Segal, A., Tversky, B. and Black, J. (2014). Conceptually congruent actions can promote thought, *J. Appl. Res. Mem. Cogn.* **3**, 124–130. https://doi.org/10.1016/j.jarmac.2014.06.004

Shoval, E. (2011). Using mindful movement in cooperative learning while learning about angles, *Instruct. Sci.* **39**, 453–466. https://doi.org/10.1007/s11251-010-9137-2

Simonetti, M., Perri, D., Amato, N. & Gervasi, O. (2020). Teaching math with the help of virtual reality, in: *Computational Science and Its Applications – ICCSA 2020: Proceedings of the 20th International Conference*, Part VII, pp. 799–809. doi: 10.1007/978-3-030-58820-5_57

Siu, A. F., Chase, E. D. Z., Kim, G. S.-H., Boadi-Agyemang, A., Gonzalez, E. J. and Follmer, S. (2021) Haptic guidance to support design education and collaboration for blind and visually impaired people, in: *Design Thinking Research: Translation, Prototyping, and Measurement*, C. Meinel and L. Leifer (Eds), pp. 167–180. Springer, Cham, Switzerland. https://doi.org/10.1007/978-3-030-76324-4_9

Smith, C. P., King, B. and Hoyte, J. (2014). Learning angles through movement: Critical actions for developing understanding in an embodied activity, *J. Math. Behav.* **36**, 95–108. https://doi.org/10.1016/j.jmathb.2014.09.001

Sober, S. J. and Sabes, P. N. (2003). Multisensory integration during motor planning, *J. Neurosci.* **23**, 6982–6992. https://doi.org/10.1523/JNEUROSCI.23-18-06982.2003

Stenning, K. (1998). Distinguishing semantic from processing explanations of usability of representations: applying expressiveness analysis to animation, in: *Intelligence and Multimodality in Multimedia Interfaces: Research and Applications*, J. Lee (Ed.). AAAI Press, Menlo Park, CA, USA.

Stranger-Johannessen, E. (2018) Exploring math achievement through gamified virtual reality, in: *Lifelong Technology-Enhanced Learning. EC-TEL 2018*, V. Pammer-Schindler, M. Pérez-Sanagustín, H. Drachsler, R. Elferink and M. Scheffel (Eds), Lecture Notes in Computer Science, Vol. 11082, pp. 613–616. Springer Nature Switzerland, Cham, Switzerland. doi: 10.1007/978-3-319-98572-5_57

Tinelli, F., Anobile, G., Gori, M., Aagten-Murphy, D., Bartoli, M., Burr, D. C., Cioni, G. and Morrone, M. C., (2015) Time, number and attention in very low birth weight children, *Neuropsychologia* **73**, 60–69. https://doi.org/10.1016/j.neuropsychologia.2015.04.016

Tomassini, A., Gori, M., Burr, D., Sandini, G. and Morrone, M. C. (2012). Active movement restores veridical event-timing after tactile adaptation, *J. Neurophysiol.* **108**, 2092–2100. doi: 10.1152/jn.00238.2012

Varela, F.J., Thompson, E. and Rosch, E. (1991). The embodied mind: Cognitive science and human experience. Cambridge, MA: MIT Press. Vercillo, T., Burr, D., Sandini, G. and Gori, M. (2015). Children do not recalibrate motor-sensory temporal order after exposure to delayed sensory feedback, *Dev. Sci.* **18**, 703–712. doi: 10.1111/desc.12247

Vercillo, T., Burr, D., Sandini, G. and Gori, M. (2015). Children do not recalibrate motor-sensory temporal order after exposure to delayed sensory feedback, *Dev. Sci.* **18**, 703–712. doi: 10.1111/desc.12247

Volpe, G. and Gori, M. (2019). Multisensory interactive technologies for primary education: from science to technology, *Front. Psychol.* **10**, 1076. doi: 10.3389/fpsyg.2019.01076

Volta, E., Niewiadomski, R., Olugbade, T., Gilio, C., Cocchi, E., Berthouze, N., Gori, M. and Volpe, G. (2019). Analysis of cognitive states during bodily exploration of mathematical concepts in visually impaired children, in: *2019 8th International Conference on Affective Computing and Intelligent Interaction (ACII)* pp. 1–7. doi: 10.1109/ACII.2019.8925521

Vygotsky, L. (1978). Interaction between learning and development, in: *Mind and Society: The Development of Higher Psychological Processes*, M. Gauvain and M. Cole (Eds), pp. 79–91. Harvard University Press, Cambridge, MA, USA.

Walkington, C., Boncoddo, R., Williams, C. Nathan, M. J., Alibali, M. W., Simon, E. and Pier, E. (2014). Being mathematical relations: Dynamic gestures support mathematical reasoning, in: *Learning and Becoming in Practice: Proceedings of the Eleventh International Conference of the Learning Sciences*, Vol. 1, W. Penuel, S. A. Jurow and K. O'Connor (Eds), pp. 479–486. University of Colorado, Boulder, CO, USA:

Welch, R. B. and Warren, D. H. (1980). Immediate perceptual response to intersensory discrepancy, *Psychol. Bull.* **88**, 638–667. https://doi.org/10.1037/0033-2909.88.3.638

Weisberg, S. M. and Newcombe, N. S. (2017). Embodied cognition and STEM learning: overview of a topical collection in CR:PI, *Cogn. Res. Princ. Implic.* **2**, 38. doi: 10.1186/s41235-017-0071-6

Woods, A. T. and Newell, F. N. (2004). Visual, haptic and cross-modal recognition of objects and scenes, *J. Physiol. Paris* **98**, 147–159. https://doi.org/10.1016/j.jphysparis.2004.03.006

Woods, A. T., Moore, A. and Newell, F. N. (2008). Canonical views in haptic object perception, *Perception* **37**, 1867–1878. https://doi.org/10.1068/p6038

Yiannoutsou, N., Johnson, R. and Price, S. (2018). Exploring how children interact with 3D shapes using haptic technologies, in: *IDC '18: Proceedings of the 17th ACM Conference on Interaction Design and Children*, pp. 533–538. https://doi.org/10.1145/3202185.3210771

Zacharia, Z. C. and Michael, M. (2015). Using physical and virtual manipulatives to improve primary school students' understanding of concepts of electric circuits, in: *New Developments in Science and Technology Education*, M. Riopel and Z. Smyrnaiou (Eds), Innovations in Science Education and Technology, Vol. 23, pp. 125–140. Springer, Cham, Swotzerland.

Figure 1 (A) Picture of children exploring new ways to represent angles with the body. (B) Groups of children working to create a shape composed of multiple angles.

Figure 2 (A) Visual angles used in the task. From the left, the angles were: 100°, 60°, 40°, 20°, 10°; each line composing the angles is 6.5 cm long. Participants were asked to indicate the visual stimulus that corresponds to the heard auditory stimulus. (B) Each data point indicates the average of each response rating's probability distribution corresponding to the response options. Error bars indicate the 95% confidence interval. One asterisk (*) indicates $p < 0.05$, two asterisks (**) indicate $p < 0.01$. With permission from Cuturi *et al.* 2020.

Figure 3 (A) A screenshot of the activity developed for exploring angles. A child must reconstruct the angles contained in a complex shaper (the house). The provided visual feedback is represented: the white angle is the angle the child' forms with her arms. The final composition of angles creates a house. (B) A child engaged in the activity.