Developing a Pedagogical Framework for Designing a Multisensory Serious Gaming Environment

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ABSTRACT

The importance of multisensory interaction for learning has increased with improved understanding of children's sensory development, and a flourishing interest in embodied cognition. The potential to foster new forms of multisensory interaction through various sensor, mobile and haptic technologies is promising in providing new ways for young children to engage with key mathematical concepts. However, designing effective learning environments for real world classrooms is challenging, and requires a pedagogically, rather than technologically, driven approach to design. This paper describes initial work underpinning the development of a pedagogical framework, intended to inform the design of a multisensory serious gaming environment. It identifies the theoretical basis of the framework, illustrates how this informs teaching strategies, and outlines key technology research driven perspectives and considerations important for informing design. An initial table mapping mathematical concepts to design, a framework of considerations for design, and a process model of how the framework will continue to be developed across the design process are provided.

CCS CONCEPTS

• Applied computing → Education → Interactive learning environments • Human-centered computing → HCI theory, concepts and models • Social and professional topics → User Characteristics → Age → Children

KEYWORDS

Interaction design, Education, Participatory design, Ubiquitous and mobile computing.

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1 INTRODUCTION

The past two decades have seen an increasing exploration into the use of technology for supporting teaching and learning, with a recent emphasis on multimodal and multisensory interaction. This has coincided with technological progress and development, which has expanded the potential to exploit sensory forms of engagement within learning. Alongside this, renewed interest in embodied cognition and interaction emphasises the role of experience, the sensory body, emotion and social interaction for cognition and learning. The use of sensory modalities to teach elementary school children also derives from renewed neuroscientific understanding about how sensory modalities interact and are integrated during development. Teaching and learning practices should reflect this scientific evidence, by introducing novel pedagogical methodologies grounded upon it. In particular, these perspectives support an embodied and enactive pedagogical approach, using different sensory-motor feedback (audio, haptic, and visual) to teach concepts to primary school children. Since the use of movement has been shown to deepen and strengthen learning, retention, and engagement [25, 38], an embodied and enactive approach would be more intuitive, being based on the experience of, and perceptual responses to, motor acts.

Critiques of technology-driven approaches to design and development of novel digital learning environments suggest that the design should instead be pedagogically driven: that the affordances of the technology should be mapped to pedagogical principles. This has implications for both the methodology and the development of a pedagogical framework.

WeDraw (http://www.wedraw.eu) is a two-year project which aims to mediate the teaching of primary school mathematical concepts, such as geometry and arithmetic, through the design, development and evaluation of multisensory serious games, using a combination of sensory interactive technologies. This approach will integrate visual, sound and haptic feedback, in response to whole body movement. In so doing it aims to enable children to better, or differently, engage with challenging concepts, allowing them to explore in ways that lead to new forms of thinking.

Furthermore, it offers new opportunities for visually impaired children through the provision of additional stimuli [19].

Methodologically we are taking a design based research approach, employing participatory design techniques in an iterative design process, working closely with teachers. To date participatory design workshops have been used to support teachers in identifying key challenging mathematical concepts for children aged 6-10, and developing initial design ideas that foreground multisensory forms of interaction. Lesson observations are used to identify key considerations for the successful embedding of the games in the classroom, and determining how they can support and compliment the teaching activity that is already taking place.

Pedagogical considerations are defined by drawing on relevant theoretical approaches to teaching and learning, and technology design approaches that supporting learning (for example, from serious games and digitally augmented environments research). Digital environments, and learning activities need to deliver more than just an enjoyable experience: each game-based activity, and use of specific modalities, must reinforce an aspect of the mathematical concept being explored, and be integrated with the expectations of schools, parents and teachers, as defined by the school curriculum. This paper describes how we have developed a preliminary pedagogical framework, intended to inform the design of a multisensory serious gaming environment for the WeDraw project.

2 PEDAGOGY DRIVEN DESIGN

Pedagogy underpins teaching and learning approaches. There are different pedagogies, which generate different kinds of teaching strategies, but what is important is choosing appropriate pedagogies for a specific time and place [60] and audience. The key consideration is achieving pedagogically driven design – rather than technologically driven design. In this way, the design "can be informed both by pedagogical theories and experiences from educational practice" [p.431 , 39].

Little work has been done to date to formally develop pedagogical frameworks in order to inform the design and development of digital learning environments [39]. Starr-Glass [67] describes a pedagogical framework as "the integrated set of philosophical considerations, teaching preferences, and learning values that informs and motivates the instructor in designing and facilitating a learning experience". These considerations are transformed into strategies or approaches for achieving specific educational outcomes. To inform digital design, the framework also needs to take into account the technological affordances in relation to pedagogy and learning design guidelines emerging from research literature.

A variety of approaches have been used to apply key pedagogical principles to design. Laanpere et al [39] propose a conceptual and process model, focusing on four contemporary notions of learning: self-directed learning (fostering interaction and linking to interface design /usability); competence-based learning; collaborative knowledge building; and task-centered instructional design (situating in an authentic context with problem based activity). Radcliffe [56] advocates the use of a set of guiding questions, for example, "What type(s) of learning and teaching are we trying to foster and why? Why is this likely to make a difference to learning? What is the theory and evidence?" Other approaches draw on notions of 'affordance', both technological and pedagogical, combined with theory to identify pedagogical principles and underpin the pedagogical framework (for example see [39, 50]).

3 THEORETICAL ASSUMPTIONS FOR MULTISENSORY LEARNING

Instructional technology environments are grounded in epistemological frameworks considered to be effective for teaching and learning. Psychologists and philosophers have long argued for the role of sensori-motor interaction with the world in cognitive development [12, 45, 51, 69]. Recent changes in thinking across other disciplines further emphasise the role of embodiment in cognition, including neuroscience [16, 21], Artificial Intelligence [4], Human Computer Interaction [18, 73], linguistics [40], and gesture studies [22]. There is increasing evidence that sensori-motor experience and interaction with the environment are central to meaning making and conceptual understanding [5, 7, 62, 66, 72], and provide the basis for learning.

Research shows that during the first years of life, sensory modalities communicate with each other, and the absence of one sensory input impacts the development of others [23]. According to cross-sensory calibration theory, in children under 8-10 years, the most robust sensory modality calibrates the others [24]. This suggests that some sensory modalities are more suitable than others to convey specific information, and hence to teach specific concepts. For example, children use the tactile modality to perceive the size of objects and the visual to perceive their orientation. Recent findings show that children start to integrate multisensory information only after 8-10 years of age [15]. There is substantial evidence that mathematical cognition is embodied [33, 40], since it is grounded in the physical environment, and based on perception and action [3]. These perspectives highlight the importance of multi-sensory, situated, experiential and discovery forms of learning.

Several studies show the benefits of embodied learning approaches in primary mathematics (for example, [22, 42]). Lakoff & Nunez [40] propose that mathematical concepts are grounded upon bodily experiences, such as manipulation of collections of objects, or physical movement in a linear path that link to ideas of grouping and number line. Educational research in mathematics has reported ways in which 'action' plays a role in teaching and learning [1, 3, 22, 47]. A central component of this is 'enactment'. Barsalou [7] highlights the importance of re-enaction of modality specific experiences: "Just as thinking about (or recognizing) a cup might involve sensorimotor preparation for grasping or drinking, thinking about an equilateral triangle might involve covertly re-enacting modality-specific experiences of physical measurement or the construction of geometric objects" [p.210 , 7].

Similarly, gestures and simulated actions provide evidence of mathematical reasoning [31]. Fostering specific actions that relate to the gestures of those who correctly explain a mathematics problem helps children to learn mathematics [22]. While 'actions' benefit from being accurate, they also need to be congruent, and through this, become meaningful in relation to the concept being learned [35, 39]. Wiemers et al. [71] showed that participants performing mental arithmetic tasks involving addition and subtraction, solved more problems when their upward and downward movements or movements to right and left were congruent with magnitude than when incongruent.

Similar effects of action and gesture have been shown for learning geometry [20, 37]. However, Walkington et al. [70] report greater transfer of knowledge to new problems when using full-body gestures compared to only hand gestures, arguing that full-body gestures better highlight how the actions relate to the relevant concepts and constraints. Similarly, second and third grade children learning about angles through mindful movements outperformed those learning verbally [63]. The movements being performed by the learners allowed for the concepts to be encoded, and their reasoning to be externalised, cementing their learning. Ma [41] highlights two important 'bodily' design features: *(i)* students' own bodies, "sometimes simultaneously, became mathematical objects (e.g. endpoints of line segments)"; and *(ii)* their bodily interactions "supported communication and negotiation of mathematical ideas (e.g., mathematical meaning was given to visible and tactile phenomena)" [p.159 , 41]. The 'body' therefore serves a dual purpose: representational meaning that is externally visible and accessible to others (e.g. an angle); and a contribution to the phenomena being explored (e.g. triangle/shape).

Three other research findings are worthy of noting. Firstly, it is important to foster reflection around action to effectively support learning [43, 65]. Secondly, using multiple physical manipulatives and pictures emphasises transference between modalities in order to teach concepts of unit, fraction equivalence and comparison [10]. Thirdly, the need for digital augmentation to go beyond what is possible in the 'real' world, introducing opportunities for collaboration, which fosters improved motivation, learning outcomes and social skills [34].

Drawing on these theoretical perspectives, and associated research to date, we can identify key aspects of embodiment that contribute to our pedagogical considerations:

1. Body-based, sensori-motor experiences
2. Collaborative and multi-user activities (visible body)
3. Use of multisensory and multimodal resources
4. Meaningful gestures, actions and movements in relation to the mathematical concept

4 TECHNOLOGY DESIGN CONSIDERATIONS

Physical manipulatives, wearable computing, haptic devices and other sensor-based technologies bring a number of affordances for interaction, and fostering embodied multisensory forms of learning. Physical objects, action and movements placed upon the objects, or bodily movement and gestures enacted freely in space can be embedded with computational power and coupled with digital information. Augmenting objects and action can be realised by flexible linking of interaction to digital information through a variety of modalities, including visual, aural and tactile. This offers new opportunities for learning, e.g. making the invisible visible, the inaudible audible, the implicit explicit, and making salient important aspects of a concept. The notion of digital feedback is linked to digital augmentation in the sense that 'augmentation' is a form of implicit feedback, where the emphasis is on designing explicit feedback to scaffold both interaction and the learning idea.

Location/spatial technologies enable spatial representation of information, and allow users to control information through spatial behaviour [58]. They provide opportunities for design to encourage specific movement in relation to mathematical concepts, e.g. moving forwards or backwards in relation to number line concepts. Tangible and haptic technologies offer new opportunities for augmented simulation, particularly in enabling physical experience through manipulation or experience of force, pressure and kinesthetic interaction. Emergent technologies enable communication to take place between devices, people and actions, enabling designs that foster collaboration, social interactivity, and aggregation, where information across devices is gathered by a central server, and distributed [58].

Many successful computer based tools can aid learning and exploration of mathematical concepts, for example ScratchMaths which combines maths with computational thinking [9] or the dynamic geometry tool GeoGebra [27]. However, they are often designed for a single user and largely based on interaction with a flat screen. While there is a body of work around tangible, whole body interaction and digital games, consideration of serious games is often limited to video games, played on a desktop computer. However, this reduces the affordances available for multisensory learning. Since WeDraw aims to embed a multisensory experience into a strong game narrative, here we outline some key design guidelines derived from contemporary research on serious games and digitally augmented learning environments, that are valuable in informing the design considerations for WeDraw.

4.1 Serious Games Research

Games and play are an important part of the social and cognitive development of young children [48]. Consciously designing games that can function as a vehicle for learning 'serious' (i.e. non-game) content can motivate learners in new ways [52]. Serious games fulfil many of the goals of constructivism [11] and there is empirical evidence that they can promote learning in secondary and higher education [32, 44]. Gameplay has been found to yield significant effects on maths performance, promoting test-based cognitive learning achievement [35]. Serious games initiatives which focus on deeper learning in the context of an enjoyable experience are more likely to succeed in their pedagogical aims [58], but a serious game will not succeed just because it has educational content. The game must be engaging and motivating: an idea that is encapsulated by the phenomenological concept of 'flow' [46], which has two main conditions: *(i)* perceived challenges, or opportunities for action, that stretch (neither overmatching nor underutilising) existing skills; and *(ii)* clear proximal goals and immediate feedback about the progress that is being made. Mapping of perceived challenge and skill identifies three regions of experience; flow being achieved when capabilities and challenge are balanced (**Figure 1**). Maintaining this balance throughout the gaming experience allows a player to stay in the channel of flow and maintains their motivation to keep playing. To achieve this, instructional game designers need to understand how game characteristics, competition and goals, rules, challenges, choices, and fantasy, used in both edutainment and serious games, can influence motivation and facilitate learning.

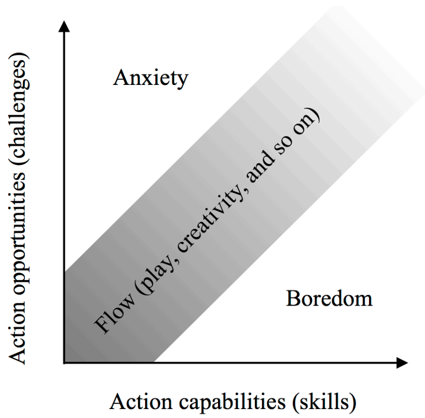

Figure 1. The original model of flow state [46]

Charsky [11] outlines some key considerations for designing a serious game for pedagogy:

1. **Goals**: game goals should match the learning goals.
2. **Rewards**: gamers are rewarded with feedback that comes in varying forms and degrees of usefulness, such as new tools, currency, access to new game spaces, people, or levels, or the very typical increase in points.
3. **Competition**: can be fostered between teams, which encourages collaboration, and has been shown to be effective in promoting positive maths attitudes [35].
4. **Duration**: longer gameplay periods can provide learners with opportunities to achieve more complex learning goals, but only if motivation is maintained.
5. **Rules**: constraints that limit the actions a gamer can take outline the boundaries of educational concepts, the rule structure provides practice on a skill set.
6. **Choice**: the number of options and decisions a gamer has prior to and during game play. Choices can be expressive (to aid motivation), strategic (the gamer's ability to change game attributes such as level of difficulty), or tactical (e.g. the decision to ''branch'' off from one narrative line to an alternative plot, or to more difficult content).
7. **Challenge**: the challenges should be designed to fulfil learning goals, whilst maintaining 'flow'.
8. **Fantasy**: a creative narrative that provides motivating and exciting game play, and cohesion for different levels or modules.
9. **Fidelity**: using graphics, audio, video, three-dimensional virtual worlds and artificial intelligence to authentically represent reality.

Educational games need to be designed with attention to contemporary learning theories, including customisation of task difficulty to the learner's capabilities, metacognitive reflection on the learning taking place, and consideration of the rich situated interaction among learner, game environment and classroom environment [74]. To succeed in its aims, a serious game must achieve pedagogical aims, social interaction and game characteristics.

4.2 Digitally Augmented Learning Environments

A substantial body of interdisciplinary research identifies key design considerations for mobile, tangible and sensor-based learning environments, drawing on both theory and empirical studies, engaging in participatory design processes, and where possible, with end users 'in the wild'. Key considerations include the design of physical-digital couplings, physical location and timing of digital feedback; design of feedback and associated mapping to movement and concept; fostering meaningful interaction, exploration, collaboration and interpretation.

The distance in space between physical and digital components of the system influences attention, interaction and interpretation. In tangible environments, the close coupling of object to digital effect is important in terms of making links between object, action and representation i.e. any information presented alongside physical manipulatives needs to be as close to the physical manipulative as possible, rather than, for example, on a separate piece of paper that needs to be separately attended to [14, 53, 55, 68]. In whole body interaction (WBI), spaces combining visual floor projections simultaneously with wall projections gives rise to conflicts in visual attention demands. Whilst each are instrumental in guiding action, this splits attention, and reduces the ability to make important mappings between action and digital output. However, the use of audio in combination with visual offers a way of focusing attention and can result in better linking of action and effect [59].

In a classroom of children, who only have a finite lesson time, it is important that each child can participate in the activities. Educational research has found that working in pairs or small groups can have beneficial effects on learning and development, particularly in early years and primary education [8], however achieving the conditions for effective group work in the classroom is more difficult. A wall projection of action and events has been shown to be valuable for observers, although it is critical that the experience is made explicit and accessible to observers, in ways that provide the opportunity for co-participation or social interaction [26]. Tangible and WBI environments have been shown to foster collaborative learning, specifically through increased awareness of others' actions [28, 54]. Hornecker and Burr [29] talk about notions of embodied facilitation and spatial interaction, which highlight the design of the space in relation to the interactive devices in shaping social interaction.

A substantial amount of work has looked at information flow: links between action, intention and feedback, primarily in relation to the metaphors or meaning embedded in the actions, objects and digital effects. Hornecker & Dunser [30] highlight the importance of matching the physical affordances of objects and actions, with the actual capabilities of the digital system, and with users' understanding of the interaction. For example, physical blocks on a tangible tabletop can be tracked on the surface, but not if lifted or set on top of another block. In these contexts, activities need to be designed that constrain actions accordingly. Antle [6] highlights three forms of mappings:

1. Perceptual mappings, e.g. between the appearance of physical and digital artefacts and representations;
2. Behavioural mappings, that take into consideration children's understanding of cause-effect relationships, including temporal and spatial contiguity;
3. Semantic mappings, which consider children's understanding of the meaning of their action and associated representations.

Notions of 'metaphor' stem from semantic mappings and are critical since they also underpin abstract learning topics. This suggests the need to carefully consider the metaphor being used in conveying the learning topic, mapping this to the design of the system. Mappings can fall on a continuum between direct and ambiguous, and need to be designed to be 'meaningful' [54]: meaning being strongly influenced by real world and familiar experiences [55]. Mappings deemed as 'persistent' [61] typically form a solid frame for the interaction. Our everyday experiences cannot always provide opportunities to encounter, embody and then rehearse the underlying aspects of mathematical concepts [2]. Crafting specific experiences through the use of physical materials is effective, provided that the physical representation adequately encompasses all conceptual features [13]. For example, in a study of low income pre-schoolers, Siegler and Ramani [64] found that playing a linear numerical board game improved performance in numerical estimation and numerical magnitude, when compared to playing numerical board games that did not correspond to number representation. This highlights the importance of correspondence between representation/action and metaphorical mapping to mathematical concepts.

5 WEDRAW PEDAGOGICAL FRAMEWORK

It is important that design scenarios take into account the evolution of mathematical concepts as outlined in the school curriculum. Game content must draw on the issues that are fundamental to understanding children's learning of mathematics [48]. To ensure that children remain sufficiently motivated, and in a state of flow, the challenge must be appropriate to the age of the child for the concept identified. Thus, for WeDraw, the key foundation for the pedagogical framework is the set of mathematical concepts outlined in the Nation Curriculum for 6-10 year olds, and digital activities will be designed around this. Within this, a subset of topics deemed to be most challenging for children to understand, that also seemed to be suitable for exploration through a multisensory game environment, were identified through a series of workshops and questionnaires involving teachers from the UK and Italy [19], supplemented by classroom observations. Further concept specification and desired learning outcomes were drawn from UK Curriculum documents [17] and a Nuffield Foundation report [49], specifically identifying relevant key pedagogical challenges for primary school maths learning.

5.1 Framework Development

The initial framework aimed to map specific ideas from the mathematical topics identified, through to design considerations in a table format. For example, see **Figure 3**, which illustrates this with respect to symmetry. Applying the expectations of the National Curriculum, we see that there are two distinct phases within the age group we are considering. The ability to identify the line of symmetry in simple 2D shapes is an expectation for 6 year olds, when symmetry is introduced in year 2. However, this is expanded in year 4, where from the age of 8 children are expected to be able to make the same identification for shapes with different orientations, and be aware that some shapes have more than one line of symmetry. They must be able to complete the mirror reflection for a half a shape (**Figure 2**). This has implications for a serious game designed to support understanding of symmetry for primary school children, as there is a clear difference between the expectations for 6 year olds compared to 8 year olds. The game needs to allow younger children to explore the concepts at a level where they are comfortable, whilst allowing challenge for children who have started to explore the next phase of symmetry. This is something that technologists and game designers may have less understanding of, but has important implications for game design. For example, indicating where the differences between different levels of difficulty might be set, or whether different versions of the game might be required for different age groups.

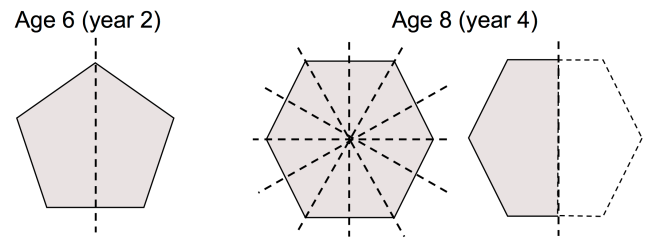

Figure 2. Year based curriculum requirements for comprehension of the concept of symmetry

Whilst this approach taken in Figure 3 was useful, it was felt to be too linear. In conjunction with teaching strategies and mathematical metaphor, the pedagogical design needs to take into consideration the affordances of the technology, and the design considerations derived from recent relevant research. As our thinking progressed, we developed a framework that illustrates the different aspects that are useful in informing the pedagogical affordances and design features that should be applied to each serious game activity, related to a specific mathematical concept (**Figure 4**). In essence, key teaching and learning strategies are derived from the pedagogical model (drawn from relevant theories of learning); and relevant metaphorical ideas are identified in relation to each mathematical concept, as expressed in the curriculum for the age group being considered. For example, if we are thinking about fractions, then the metaphor of 'partitioning' is considered valuable in conceptualising whole to part ideas. This metaphor can then inform the kinds of bodily actions or gestures to be designed - ones that involve 'partitioning'. If we are thinking about positive and negative numbers in the Cartesian plane, then we need a metaphor for representing and moving between negative and positive numbers, where the negative number is meaningful in itself and not just a product of subtraction. One metaphor for this might be temperature.

Specific challenges from teachers	Mapping to curriculum/ year group	Pedagogical considerations	Key Design considerations
Symmetry: **Considered easier for simple shapes such as circles and triangles but challenging once the shape becomes more complex.**	Age 6 (year 2): • Requirement: Identify & describe properties of 2-D shapes, including line symmetry in a vertical line. Age 8 (year 4): • Requirement: Identify lines of symmetry in 2-D shapes, in different orientations. • Requirement: Complete a simple symmetric figure with respect to a specific line of symmetry.	• Understand the concept, what symmetry means. • Understand the lines of symmetry - becoming familiar with different orientations of lines of symmetry. • Understand the points of connection in a shape and how they might map to a line of symmetry. • Perspective taking capability is important.	Considerations • Which body actions, gestures or whole body interactions enable representation of shape? Which shapes? Collaboration? • How to explore the shape to determine if there is a line of symmetry (important that shapes without can also be explored) and where it might sit with respect to the shape. • How to meaningfully augment the shape with a chosen line of symmetry. • How to feedback during exploration?

Figure 3. Example of an initial WeDraw pedagogical framework consideration: symmetry

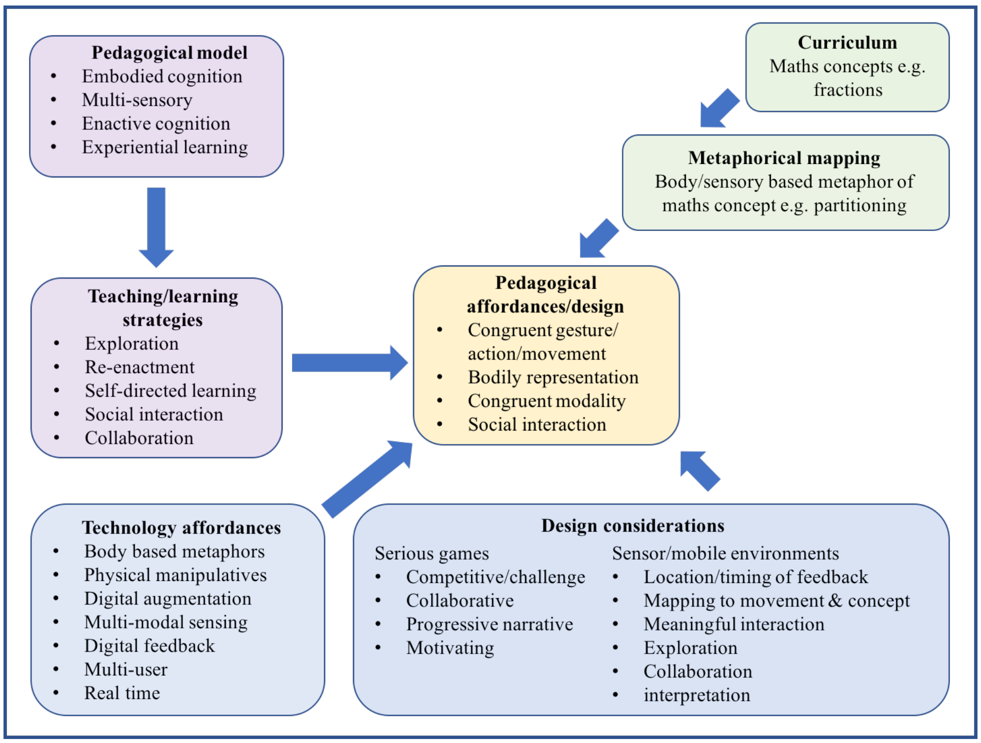

Figure 4. Initial Pedagogical Framework

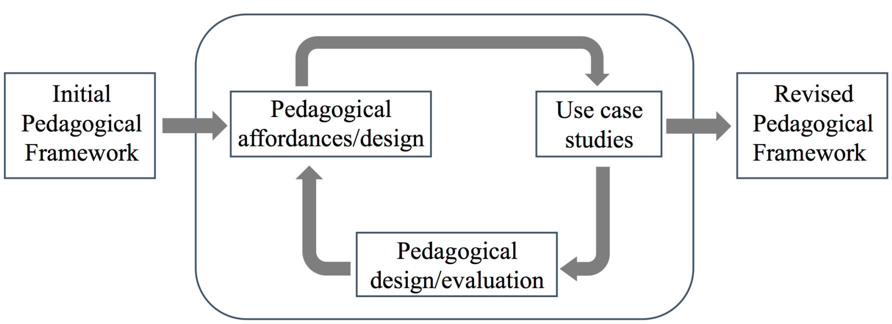

Figure 5. Process for pedagogical framework development

For the WeDraw project, the pedagogical framework shown in **Figure 4** will be incorporated into an iterative design process used to develop technology use cases for prototype games, as shown in

Figure 5. These will be evaluated, both at the conceptual stage with teachers, and in the form of technology prototypes that will be evaluated with the users (teachers and children). At each stage of evaluation, the pedagogical affordances will be reconsidered based on the results, whilst maintaining reference to the initial pedagogical framework. Studies will be designed to explore how children explore the pedagogical concepts, that will form part of the affordances/design stage, and inform the use cases. For example, designing simple games that encourage children to solve problems of symmetry together in pairs, in order to understand the language, gestures and body movement that are used by each age group. Since the ambition of WeDraw is to develop a series of multisensory serious games, these studies will inform the use of different sensory inputs (such as whole body movement) and feedback (e.g. haptic, visual, audio).

6 CONCLUSION AND NEXT STEPS

The aim of the pedagogical framework is to illustrate that the theory of learning (pedagogical underpinning) leads to consideration of instructional strategies that involve the 'body', through a multisensory serious games design, which is also informed by appropriate mathematical metaphors and technology design guidelines, in building meaningful connections between physical action and concepts in early years' mathematics. The framework will continue to be developed across the project with two key aims:

1. To develop the pedagogy driven design process to inform and extend the overall pedagogical framework.
2. To use the framework to identify detailed individual pedagogical affordances and design requirements for each mathematical concept, and serious games module, developed across the project. These will specify the kinds of actions/gestures, modes of augmentation and feedback, in relation to the mathematical concept/ metaphor and the pedagogical model, for each activity.

The workshop forum should provide opportunities for discussion around these initial ideas, that will support the ongoing development of a pedagogical framework for designing multisensory serious games to support the teaching and learning of young children's mathematics.

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