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# Everyday Access to Abstract Concepts: The Potential of Metaphor-Based Embodied Interactions and Learning

## Introduction

To many, learning is associated with passively sitting at a desk, listening, and taking notes. As a recent public-school teacher in Montgomery County, Maryland, my students were provided Google Chromebooks to use in class and at home. Many teachers transferred pencil and paper lessons to the Chromebooks, resulting in students typing answers instead of handwriting them. There were no new methods taking advantage of the Chromebooks' potential or creating content requiring bodily engagement in ways that got students out of their seats. In this paper I will attempt to answer the following research question: How does metaphor-based embodied interaction affect the learning recall of abstract concepts? Using 16 papers, I will argue for the importance of creating metaphor-based embodied interactions that are not intuitive, but instead have designed shortcomings for initial discoverability to create frequent shifts between experience and reflection to enhance the learning of abstract concepts.

## Background

In their seminal work on metaphor, Lakoff and Johnson (1981) argue that metaphors are not just words, but instead are a large part of the process of thinking. Lakoff and Johnson (1981) identify structural metaphors as "cases where one concept is metaphorically structured in terms of another" (p. 22). Orientational metaphors are related to spatial orientation and "arise from the fact that we have bodies of the sort we have and that they function as they do in our physical environment" (Lakoff and Johnson 1981, p. 22). Examples of orientational metaphors are up-down, in-out, on-off, etc. that are built from our everyday bodily experiences. Ontological metaphors provide "ways of viewing events, activities, emotions, ideas, etc., as entities and substances" (Lakoff and Johnson 1981, p. 35). Ontological metaphors like "he broke down", using "the mind is an entity" metaphor are so pervasive that they are taken as direct descriptions of psychological events instead of being seen as metaphorical (Lakoff and Johnson 1981). This paper will investigate how the process of uncovering awareness about everyday metaphors can be leveraged for learning.

Another important metaphor-related term to understand the papers below is image schema. An image schema was defined by Johnson (1987) as "a recurring, dynamic pattern of perceptual interactions and motor programs that gives coherence and structure to our experience" (p. xiv). For example, experiencing gravity and observing its effects forms the UP–DOWN image schema (Hurtienne et al. 2010, p. 1). Image schemas become primary metaphors through repeated experiences of "concrete physical sensorimotor experiences with more abstract subjective experiences" (Hurtienne et al. 2010, p. 2). Watching the water rise in a glass while you are filling it up and other similar experiences contribute to the formation of the "more is up – less is down" primary metaphor. 250 primary metaphors have been identified that combine image schemas and abstract concepts (Hurtienne et al. 2010). Hurtienne et al. (2010) state that because primary metaphors are formed from repeated experiences, it means "interaction based on primary metaphors should be largely independent from conscious abilities like the speed of information processing" (p. 3). This is important for our investigation as conscious resources do not have to be devoted to understanding the metaphor as it is already understood at a subconscious level, leading to more energy being devoted to embodied interaction. This is also important to our investigation as speed of processing must be designed to not be too overwhelming in the initial exploratory stages of an embodied interaction.

Dourish (2001) wrote a foundational work on embodied interaction. He argues that embodied interaction "is interaction with computer systems that occupy our world, a world of physical and social reality, and that exploit this fact in how they interact with us" (Dourish 2001, p. 3). Dourish refers to the computer systems that represent the physical reality of our world as tangible computing. Dourish refers to the computer systems that represent the social reality of our world as social computing. Dourish believes our everyday world is made up of physical interactions with artifacts and social interactions with people and customs. Tangible computing "attempts to move computation and interaction out of the world of abstract cognitive processes and into the same phenomenal world as our other sorts of interactions" (Dourish 2001, p. 103). The same artifacts we use in our everyday lives can be used for interaction opportunities with computers. Social computing "recognizes that meaning is something that users create through the ways in which they interact with technology and with each other" (Dourish 2011, p. 128). For Dourish, meaning can be negotiated while interacting with software systems, allowing "users to create and communicate the meaning of the actions they perform, rather than struggle with rigid meanings encoded in the technology itself" (Dourish 2001, p. 127). This is important for our investigation as freeing the body from interaction restrictions is important in initial stages.

A study that represents metaphor-based embodied interaction and inspired this investigation was performed by Antle et al. (2009a). The researchers built an interactive environment called Springboard for users to balance their bodies to investigate issues of social justice. The researchers chose balance because it was abstract and can be represented visually. The Springboard was a crib mattress spring placed on a platform. The balance schema represented was the twin-pan model. Antle et al. (2009a) designed it so "when a user steps onto the platform, their centre of gravity becomes immediately, slightly out of balance since they will likely wobble on the platform" (p. 4). Social issues were displayed on a screen that change as a user moves their body accompanied by metaphorically related changes in sound. Some of the research questions Antle et al. (2009a) were concerned with were: "Does incorporating an embodied metaphor in the interaction model make the system easier to use? Easier to learn? Easier to understand?" (p. 2). Antle et al. (2009a) were not concerned with learning the abstract content, but instead with learning the system. This is an issue we will encounter in many of the papers reviewed below. As we attempt to answer our research question, we should also ask when using metaphor-based embodied interaction to learn abstract concepts, is learning the system the same as learning the content?

**Methods**

I reviewed 16 papers. All 16 papers were found searching the ACM Digital Library for the terms "metaphor-based embodied interaction", "embodied learning and abstract concepts", "embodied learning and metaphor", "tangible user interfaces and metaphor and recall", "interaction metaphors and learning recall", and "abstract concepts and interaction". I had to go through many results to find papers helpful to answering the research question. Many of the papers relate in indirect ways and provide support for broader ideas which I grouped into the following sections: The Unlimited Body and the Limited Object, Finding the Right Representation, Remember the Effort, Time for Reflection, and Learning. Each section uses three or four papers to develop an answer to the research question in that area. After a review of the papers, I will synthesize the ideas in a discussion section arguing for the importance of creating metaphor-based embodied interactions that are not intuitive, but instead have designed shortcomings in initial discoverability to create frequent shifts between experience and reflection to enhance the learning of abstract concepts.

## Literature Review

### The Unlimited Body and the Limited Object

To attempt to answer our research question, we will first examine how metaphors can be used to interact with abstract concepts. In the studies in this section, multiple metaphors are used to interact with the abstract concepts of sound parameters. In the first study, Antle et al. (2008) defined embodied interaction as "direct, body-based interaction with computation embedded into everyday artifacts such as objects and spaces" (p. 178). The authors set out on an empirical study to investigate "how and why embodied interaction in interactive environments might enhance children's conceptual learning" (Antle et al. 2008, p. 178). Antle et al. (2008) created an interactive environment using the "music is body movement" metaphor. The system transferred the input of bodily movement to changes in the volume, tempo, and pitch of sound output. For comparison, another version of the system was built that did not use metaphor in the mapping layer between input movement and output sound change. The system was named "The Sound Maker" and used camera vision to track movement in a 5.1 x 4.5-meter space.

The Antle et al. (2008) study had 40 participants ages 7-10 with 20 males and 20 females. The participants were grouped in pairs to complete all tasks. Dyadic interactions with the Sound Maker were preferred over individual interactions because participants moving together in space is common practice in the Dalcroze Eurhythmics music education approach used to inform the study. Ten pairs of participants used the embodied metaphor and ten pairs used the non-metaphor version of The Sound Maker. Antle et al. (2008) hypothesized that the embodied system would be easier to learn. The participants were first given time to interact with the system in a free play session. Then the participants were given three tasks to create sound sequences, for example making the sound louder and then quieter again. The pairs of participants were given 10 minutes to practice their sequence for each task. Then the participants gave physical demonstrations of the sequence followed by a verbal explanation.

From the data collected, Antle et al. (2008) found practice times were not significantly different between the embodied and non-embodied interaction methods. For the accuracy of physical demonstration and verbal explanation it was found that the embodied metaphor groups scored 63% whereas the non-metaphor group scored only 7%. Antle et al. (2008) also found that participants in the embodied metaphor version physically performed the task sequences correctly 80% of the time, but only verbally explained these sequences correctly 47% of the time. Antle et al. (2008) state that this result provides evidence that participants "may be able to physically perform sequences better than they can verbally explain them" (Antle et al. 2008, p. 183). They found no clear evidence that the abstract musical concepts were better understood using the system. Researchers were also unsure if this approach was limited because it is more based on usability than learnability.

This study addresses my research question by showing that abstract sound concepts can be better understood using embodied metaphors. The study also presents the difficult distinction we will see in many other papers of how to differentiate between learning the system and learning the content. One of the shortcomings of the Antle et al. (2008) study was that differences between the demonstrated physical movements of the sound concept and the explanation might be related to learning the system and not a benefit in conceptual understanding. Another shortcoming is that Antle et al. (2008) only used children whereas adults might be better able to grasp all sound concept terms. Another shortcoming was that the authors had "no clear evidence that children came to better understand the musical concepts represented in the system" (Antle et al. 2008, p. 183). The researchers also note that they are unsure if this knowledge could be transferred by the children to other domains or situations.

Bakker et al. (2009) built on the above study by Antle et al. (2008). Bakker et al. (2009) reference embodied metaphors to embodied schemata, the repeated patterns or structures we experience with our bodies. Their research goal was to find if children's conceptual learning in abstract domains is supported by interactive systems that use multiple embodied metaphors in their interaction models. Bakker et al. (2009) studied eight concepts related to sound: volume, pitch, rhythm, tempo, timbre, harmony, articulation, and tone duration. The participants of the study were 65 children ages 7-9 from two elementary schools.

Bakker et. al (2009) assigned 3-4 exercises to each participant with each exercise involving one of the eight sound concepts listed above. Each exercise started with a 20 second sound sample that showed the extreme ends of one of the concepts. The participants were then asked to verbally explain the sound they heard. Then the participants were spread out in the room, the concept was played to them again, and then participants were asked to create a movement to show the sound they just heard. Participants were given the chance to perform the movement they created in front of the whole group of participants. Seven groups to expressed the sound concept using their whole body and four groups expressed the sound concept through tangible objects.

Bakker et al. (2009) found comparing the body vs object conditions resulted in the same metaphors being produced under both conditions. Bakker et al. (2009) suggest, "this provides support for the generalizability of the use of embodied metaphor in all interactive systems that use movement as system input" (p. 147). Bakker et al. (2009) also noted that multiple metaphors were used for one enactment in the embodied condition, but the object condition resulted in most enactments only having one metaphor. Another finding of the study was when a low number of metaphors were generated for a concept, that related to a lack of understanding of the concept. Bakker et al. (2009) also note their findings confirm what has been suggested in previous work, that abstract concepts first are understood by the bodily experience, and only after this can be explained in words.

This study addresses my research question by showing that embodied interactions afford multiple metaphors for the same abstract concept, whereas tangible interactions only afford one. This is of interest to our research question as it presents the opportunity to use different interactional metaphors for the same abstract concepts, increasing the opportunities to design and extend novel exploratory experiences with the content in a structured way. Some shortcomings of the Bakker et al. (2009) study include the finding that concepts like timbre were difficult to enact because it does not offer two opposite adjectives or extremes to animate. The study also found that some metaphors were based on spatial location within the testing area rather than the body, so the music is body movement metaphor the study was based on may not work for all sound concepts as some may be more related to spatial location than the body. A shortcoming was that children were asked to perform the movement enacting the sound concept in front of the group, so other participants had the opportunity to see it and adapt their enactments accordingly. Another limitation is the study was done on children, so there are unanswered questions about how adults might perform sound enactments and explanations during similar exercises.

Bakker et al. (2010) build on the tangible object research performed above in Bakker et al. (2009). Bakker et al. (2010) refer to embodied metaphors as “unconscious knowledge originating in body movement that can be applied automatically” (p. 85). Their research goal was to investigate “if and why interactive systems that incorporate multiple embodied metaphors in their interaction models can support children’s conceptual learning in abstract domains” (Bakker et al. 2010, p. 85). The researchers built the interactive environment Moving Sounds Tangibles that allows multiple mappings to single abstract concepts. The abstract concepts focused on in this study are pitch, volume, and tempo. Bakker et al. (2010) chose tangible interaction over whole body interaction because tangibles allow for clear differences between multiple mappings. 39 participants were recruited ages 7-9 and individually interacted with the Moving Sound Tangibles environment in 20-minute sessions.

Bakker et al. (2010) attempted to perform a quantitative analysis on the learning of abstract concepts by giving a sound knowledge test before, directly after, and six weeks after the experiment. A correlation between the results of the three tests confirmed the test was not reliable so no learning benefits can be drawn from this study. The authors note that although correlation tests are not ideal, they were the only measure they had available for testing reliability. The learning effects were then attempted to be drawn from performing a video analysis of the expressions participants used when explaining and listening to the sound samples. The authors captured 457 expressions and categorized them via open coding. From their analysis, Bakker et al. (2010) found there were no clear differences between the one and three-artifact conditions for the three abstract concepts. Bakker et al. (2010)’s study found no evidence to support multiple embodied metaphors can help children learn and structure abstract concepts. But the researchers claim because the participants did not show confusion when multiple metaphorical movements were used for the same abstract concepts, their learning experiences were not hindered. This shows there may not be one perfect metaphor for an abstract concept, but instead shows multiple metaphors may help make the concept concrete. Bakker et al. (2010) also state that because not all children were able to explain the abstract concepts using words, but all were able to recreate the sounds using the tangible artifacts, that children can use movement to understand abstract concepts they cannot yet explain through words.

This study addresses my research question by attempting to show the learning recall of abstract concepts using metaphors through tangible objects. If the results of the three tests had been reliable, it would have better aided this paper's pursuit. A gap in the research that Bakker et al. (2010) recognize is there have been very few studies on the learning benefits of tangible systems. A shortcoming recognized by the researchers is that longer term experiments need to be conducted to truly test the learning benefits of multiple embodied metaphors. Another shortcoming identified by Bakker et al. (2010) is the language of the study was Dutch which has multiple meanings for some of the metaphor pairings used such as soft and loud being used for slow and fast as well. A study performed in a language where there is no overlap in descriptive terms for abstract concept may result in a study of learning with more robust results. Another shortcoming is this study also only focused on children, whereas the experience of adults has not been studied yet.

The three papers in this section together offer a perspective on how paying attention to the body during interaction can lead to more exploration of metaphor-based interactions. Antle et al. (2008) noted "learning how to control the sound parameters required that children recognized when their movements elicited the sound effect they were trying to create" (p. 184). The children had to pay attention to their movements to discover how their movements were causing the sound to change. This attention brings the abstract concept to the body, which is then able to be understood by pairing it with a metaphorical movement. Antle et al. (2008) also found "immediate perceptual confirmatory feedback was required to leverage embodied knowledge of the metaphorical relation between natural movements and musical sound parameters" (p. 184). If the feedback was not immediate, the connection between the movement and the sound concept could be missed. For the pursuit of our paper, these initial stages when the concept is being explored by the body seem to be important and overlooked by researchers. These stages could be where the learning of the content is maximized as the user is shifting between experience and reflection before the system has already been learned.

Bakker et al. (2009) also found children would explore more with their bodies as "the children in the full-body movement condition often used more than one metaphor in their enactment, whereas mostly single metaphors were seen in the object condition" (p. 147). Metaphor-based embodied interaction allows for multiple ways of interacting with concepts, even though a lot of this interaction initially may be exploration. This is of interest to our pursuit as metaphorical thinking is boosted when we are using our whole body, leading to a more stereoscopic experience of the concept as it can be approached through multiple interactions rather than limited to one. Bakker et al. (2010) supported this finding when they recognized "tangible interaction can offer clearer affordances than whole body interactive environments, which has evidently enabled participants to quickly find out how to operate the tangibles" (p. 91). Clearer affordances offered by objects allow for quicker learning, but the exploration required to discover embodied mappings may lead to deeper learning. The papers in this section have shown that structuring the learning of the content with the learning of the system may maximize learning potential when using metaphor-based embodied interaction.

**Finding the Right Representation**

Besides audio as we saw above, there are other ways to present abstract content for learning using metaphor-based embodied interaction. Price et al. (2009) set out to investigate the usability, engagement, and collaboration created from the interaction locations of tangible learning environments. The researchers specifically focused on "location and physical correspondence and their influence on interaction and meaning making" (Price et al. 2009, p. 88). 21 children, all 11 years old worked in groups of three at a tabletop interface to explore the abstract concept of light behavior. The tabletop interface had moveable blocks on the surface that would create digital animations about the behavior of light either on the tabletop surface (co-located) or projected on a wall in front of the table (discrete). Each session was 35-45 minutes and the facilitator would prompt the participants with simple questions about what was happening to help shape their understanding of the concepts. Participants were interviewed after the experience in their groups.

Price et al. (2009) found most participants preferred the co-located version of the display that was shown alongside the tangible blocks on the tabletop. In the discrete version, participants were quieter and "their actions, or the changes made by moving the objects were slower and less frequent" (Price et al. 2009, p. 89). In an interview, one participant stated the slower feedback with the projected discrete version gave them more time to think about what was happening. This study addresses my research question by showing that slowing the interaction with the content by separating the display from the tangibles creates more time to shift between the experience and reflection to enhance learning. Using a separated discrete display is a way to design shortcomings in usability to slow down interactions and connect them metaphorically to content. Because the tabletop objects were tangible, their affordances were more quickly understood than embodied interactions, so separating the visual feedback from the object slowed the interaction in a way that created moments of explorative uncertainty and increased interest and learning. One shortcoming of this study is it focused on interaction and meaning making but not learning specifically. Another drawback is the participants were children and were working in groups as opposed to individually.

VR is another platform for metaphor-based embodied interactions. Chatain, Kapur, Sumner (2023) take a theoretical interdisciplinary approach to embodied learning activities in VR. Their study focuses on the following elements: "'embodied cognition', the role of one's body in their learning, 'embodied interaction', the role of one's body in making sense of interaction, and 'avatar embodiment', the connection between one's body and their digital counterpart" (Chatain, Kapur, Sumner 2023, p. 2). Chatain, Kapur, Sumner (2023) argue that embodied learning relies on direct state induction, modal priming, and sensorimotor stimulation. Chatain, Kapur, Sumner (2023) state learning activities should facilitate gesture production as spontaneous bodily actions are performed when thinking about abstract concepts. The researchers also note directed bodily actions help learning through directing learners to notice the results of their physical movements to make sense of concepts.

Chatain, Kapur, Sumner (2023) developed a framework for designing for embodied learning. One of the points of their framework is to "consider how the meaning of the interaction relates to the meaning of the concept being learned" (Chatain, Kapur, Sumner 2023, p. 5). The researchers note that context is also important to consider when designing for embodied cognition as it can make the information more relevant to the learner. Another aspect of the researchers' framework is designing for embodied cognition using desirable difficulties or shortcomings in usability. These desirable difficulties can happen in the gap between proximal and distal movements, which are the interaction with an object and the effect in the world respectively. Desirable difficulties can be created using temporal distance by adding delay between bodily action and feedback to make space for reflection. This study addresses my research question by supporting the importance of shortcomings in usability that slow down feedback between the interaction and the content to create space for shifts between experience and reflection. A shortcoming of this paper is that it does not discuss metaphor-based embodied interaction in detail but does mention many of the papers used in this literature review.

Content for metaphor-based embodied interaction can also be displayed on the body using AR. Chatain et al. (2020) conducted a user study on the design of DigiGlo, a digital glove system to help connect the point of interaction and content display. Chatain et al. (2020) developed three activities for their digital gloves: Space Traveller, Marble Runner, and Noelle's Ark. Space Traveller is a pinball game based in space played on the hand. Marble Runner is a rolling marble controlled by the player's hand tilts. Noelle's Ark uses intuitive hand movements to choose an object that weighs more from a pair displayed on each hand. DigiGlo allows intuitive control as it responds to natural hand movements, addresses split attention because the display and interaction are co-located, and uses embodiment as participants use bodily movement to interact rather than just seeing and listening. To test the three activities with DigiGlos two studies were done, the first focused on overall usability and the second focused on an analysis of the system and design recommendations.

From the first study Chatain et al. (2020) found the thumbs-up gesture and pinch gesture were the most enjoyed and easy to use. The second study showed many participants enjoyed how simple the interaction was. Chatain et al. (2020) noticed during the interviews "the participants used the gestures of the games as part of their description of the game," showing an embodied understanding of the interaction (p. 381). In the interviews some participants noted the small display on the hand and wondered if the display could cover their entire body. The second study found "DigiGlo requires activities to involve meaningful and simple hand gestures, which are consistent across all activities" (Chatain et al. 2020, p. 383).

Interestingly, the authors noted that fast-paced gesture input can overwhelm users, connecting to our growing investigation of designing for a slow pace to allow for reflection of the interaction with the content. The authors provided instructions about the gestures in a document to the participants before beginning the study. Most participants did not like this and had difficulty interacting with the games initially. Chatain et al. (2020) suggest a tutorial phase at the beginning of activities for both user purposes and to calibrate the system. This study addresses my research question by showing that the initial learning of the interaction methods is a vital part of embodied interaction that is overlooked by most researchers. Instead of giving users exploratory time at the beginning of each session, Chatain et al. (2020) provided a document with instructions which users did not like. Users want the ability to test and learn the system while using it, and researchers have missed the opportunity for pairing these initial learning stages of the system with learning foundational aspects of the content. A shortcoming of this study was that only one of the games, Noelle's Ark, dealt with metaphor in the balancing movement of the whole upper body for estimating the weight of objects in a twin-plate balance. Another shortcoming of the two studies is they were based on usability and not learning the content.

Metaphor-based embodied interaction can not only be done with the body and on the body, but also in the body. Daudén Roquet and Sas (2021) conducted an exploratory study which compared two forms of feedback during meditation. The aural feedback studied was provided by the Muse meditation app. The haptic thermal feedback was provided by the WarmMind prototype. The researchers' aim was "to understand how to design embodied metaphors with different feedback modalities" (Daudén Roquet and Sas 2021, p. 1). The Muse app works with a wearable headband that senses brain activity and uses aural feedback to alert the meditator that their mind is wandering. Sometimes this feedback can distract or frustrate the meditator, interrupting the intended effects of the meditation session. Daudén Roquet and Sas (2021) identified a gap in "a theoretically informed framework to support design of metaphor-based mappings of physiological data" (p. 2). The study was designed to compare aural and thermal feedback for the meditation states of being mindful, mind wandering, and shifts between the two.

The WarmMind prototype was designed to be worn around the neck with four heating pads placed from the upper chest to the navel. The metaphor used for the state of being mindful was steady warmth on all four pads. The metaphor used to represent mind wandering was chaotic movement of heat between pads in no order. The metaphor used for the change of meditation state was individual pads heating from the upper chest down to the navel in 6-second increments. The user study was conducted with 10 participants who were on average 21 years old. The participants meditated for 5 minutes and then a semi-structured interview took place. Daudén Roquet and Sas (2021) found though the aural feedback of the Muse app had better discoverability, it took the meditator's attention away from the practice and the return of attention to the breath was not direct enough. On the other hand, with the haptic thermal feedback of the WarmMind prototype, the focus of attention stayed in the body and included more awareness of the meditator's senses. The participants reported the changes in the haptic thermal feedback were hard to notice because of their subtlety and could not identify which pad was heating individually at a time.

Participants in the study found the aural feedback from the Muse App distracting because it was too intense, changed too often, and was sensorially overwhelming. If we view learning as the regulation of attention, this study supports the idea that metaphor-based embodied interaction methods should be slow to allow for shifting between reflection and experience. This study addresses my research question by showing that when the body is involved, interaction can quickly become overwhelming and distract from the learning task. Metaphor-based embodied interaction must be designed for gradual increases in feedback, creating the opportunity for the incorporation of additional metaphors and interaction methods once the system is learned to allow for the initial exploratory uncertainty of learning the system to be recreated. Daudén Roquet and Sas (2021) suggest drawing metaphors for interoceptive interaction from many areas including spiritual traditions and the phenomenology of meditation to find more appropriate metaphors. The subtle interoceptive interactions can be used to not distract users from learning tasks.

In this section, we found that multiple ways of representing the content still result in the same slow exploratory pace for learning. Price et al. (2009) noted the discrete version of the representation when the content was projected on a wall in front of the interactive table slowed the pace of the interaction with the blocks and allowed more time for reflection. Price et al. (2009) noted "the need to specifically design learning activities that slow down interaction and promote opportunities for reflection to occur during 'calm' periods at various points in the learning task" (p. 91). I agree with this need and think it could be done by structuring interaction with the content to pair with learning the system. In many of the studies the embodied interaction methods are novel to the users, and the users must explore interaction and feedback they have not experienced before. None of the studies have considered how these interactions may change once the interaction system is learned and has become second nature. If it is like other interaction methods that have become second nature, users will think less about both the content and what their bodies are doing. If multiple metaphors can be incorporated for the same abstract concepts, users can learn a new interaction method once the first method has become second nature. If abstract concepts were structured for learning across multiple metaphor-based embodied interaction methods, users may be able to recreate the initial hyperawareness of their body and feedback from the content to enable longer periods of learning.

Also in this section, Chatain, Kapur, Sumner (2023) note the importance of desirable difficulties "in interaction to support deeper sense-making of bodily actions" (p. 6). The key to embodied interaction is to think about what you are doing with the body to interact with the content. The more the interaction is slowed down, the more you must think about what your body is doing to produce changes in the content. Chatain et al. (2020) noted that users became overwhelmed if the gesture input was too fast paced. The discoverability of the mappings between movement and its effect must be gradual and built into the system. Daudén Roquet and Sas (2021) used subtle interoceptive interaction and "suggest a more nuanced understanding of supporting discoverability, strongly advocated in tangible interaction research" (p. 12). Bringing the mind back to the body and thinking about the movements we are making can help deepen learning.

**Remember the Effort**

Subtle and underwhelming metaphor-based embodied interactions can work as seen above, but what about interactions that require more physical effort? Lyons et al. (2012) set out to create guidelines to use exertion in embodied interaction designs. The authors state "the linkages between exertion, affect, and recall are reviewed and analyzed for their potential to support embodied learning activities" (Lyons et al. 2012, p. 1). The authors intended to ground effort in psychological and physiological theories. First the authors reviewed seven existing frameworks by examining their purposes, design themes, and suggestions for employing exertion in interfaces. Some frameworks the authors identified are based on dance, kinesthetics, and motion. Common themes in these frameworks are "the weight or heft of an object is often associated with metaphors like 'increasing importance'" (Lyons et al. 2012, p. 2). From the seven existing frameworks examined, the authors identified three general guidelines: "consider how effort affects performative and spectator activities", "consider how effort could map to system output", and "consider how variable effort levels could be used as an affordance" (Lyons et al. 2012, p.2). These guidelines were meant to help designers of effortful installations create learning experiences for participants and observers that are meaningfully related to the content displayed.

Lyons et al. (2012) note museums have commonly employed exertion interfaces in exhibitions for learning opportunities for more than 40 years. The authors identify a gap that little is known why exhibits use exertion interfaces to benefit learning. To explore this gap, the authors examined the psychological underpinnings of strong recall linked to exertion interfaces. Lyons et al. (2012) identify the link between arousal and affect stating that "preservation of high recall under high arousal can be attained by inducing emotion gradually through thematic narratives" (p. 4). The narrative used to shape the exertion interaction does not have to be complicated, but only needs starting and end points. The authors write humans are both consistent and accurate in their perceptions of effort, so different levels of effort can be incorporated in exertion designs.

Lyons et al. (2012) then walk the readers through the revised design of a new embodied interaction exhibit about climate change based on their findings. Some of the revisions included removing scoreboards and instead making polar bear avatars show their exertion in the form of exhaled breath. Another revision was getting rid of exercise bikes and instead using Wii remotes and a Wii balance board to have users swim between melting icebergs to better link to the climate change narrative. The authors also included docents to add narration to the exhibit experience to improve recall from more thematically induced emotions. This study addresses my research question by showing that embodied interactions do not have to be subtle and comfortable to be effective but can be physically difficult and uncomfortable if the effortful interaction is meaningfully related to the content being learned. This study the closest to the type of metaphor-based interaction I imagine being designed in the future as it relates the metaphorical effortful movement of swimming between icebergs to communicate information about climate change. Effortful interactions like this could be structured into school curriculum to allow for active bodily engagement away from desks. This study was concerned with museum installations which are not regularly visited, so the experience was meant to make a lasting impression on visitors. Future studies should consider continual engagement with effortful interfaces, for instance in a weekly gym class or a tutoring center, which could result in deeper learning of the content through conditioning. That this study also recommends simple narrative structures for effortful interactions also supports longer term interactions in the form of episodic effortful learning activities that could occur on a weekly basis like a television show. A shortcoming of this paper is there was no study, just the creation of a new exhibition based on their own research.

Malinverni et al. (2012) performed a study to test whether the Interactive Slide exertion interface supports the learning of abstract content. The abstract content for this study was the phenomena of gravity and Archimedes' principle. The authors were interested in this research because they believe learning in the digital era requires students to take a more active role than passive sitting and listening. The Interactive Slide is inflatable and 4 meters wide and 3 meters tall. Computer vision is used to detect movement on the slide surface. A virtual environment is projected on the slide's surface that can be interacted with by sliding down. Because the sliding motion is downward, the authors wanted to work with gravity and related principles. The hypothesis of their research was “to test whether the physical activity on the Interactive Slide supports the understanding of the application’s science content” (Malinverni et al. 2012, p. 63). The authors used pre and post-test questionnaires to measure learning. The experimental condition was the Interactive Slide, and the control condition was performing the same activity on a desktop computer. 331 participants were recruited between 9 and 12 years old from the 5th and 6th grades. Children in the experimental group first played an interactive game that familiarized them with the Interactive Slide.

The study found results that “suggest the possibility that the Slide could be more effective than the desktop computer as an interface for learning abstract concepts related to physics” (Malinverni et al. 2012, p. 66). The questionnaire scores of participants who used the Slide improved significantly between the pre and post-test, while the desktop participants showed no significant change. The authors state the results confirm exertion as a viable tool in education to transfer bodily experience to abstract knowledge. The authors suggest future work could better map content to the bodily engagement of sliding. The authors note the pre-test could have “played an important role in the process of upgrading from concrete experience to abstract knowledge, by altering the context situation” (Malinverni et al. 2012, p. 66). The authors suggest future research should find ways to measure implicit knowledge and learning while participants are using the exertion interface instead of giving a pre-test. This study contributes to answering my research question by again highlighting the importance of the initial stages of interaction and the learning of the system. The authors felt the pre-test altered the context of the interaction because participants became too aware of what was supposed to be learned. If the context were discovered at the same time as the interaction methods, would this allow participants to authentically explore at a pace conducive to shifting between reflection and experience? A limitation of this research is that it did not use adults to test any of the learning effects.

Another perspective on effort and the body at play was conducted by Mueller et al. (2018) who argue for two phenomenological perspectives about the body for designing bodily games. The authors identify a gap in the field that the body is viewed in too simplistic terms when interacting with games. The authors identified two ways of looking at the body: as a thing or object, or as a living body with senses and other attributes. Mueller et al. (2018) used German words to apply to the two different views of the body. The body as a physical object or a corpse is called “Körper”. The living body or lived body is called “Leib”. The authors noted that “every Leib needs a Körper, but not every Körper needs a Leib” (Mueller et al. 2018, p. 3). The authors expanded on the notion of bodily engagement with games from Körper to our Leib. An example provided by the authors for incorporating Körper and Leib in game design is the placement of the “OK” button. The Körper perspective would place the “OK” button in an easy to reach place so it can be clicked quickly and without effort. The Leib perspective would first consider the feelings produced by the action, leading to the “OK” button being placed high on the screen to cause players to strike a “winner-pose” every time they confirm something in the game.

The authors argue the important part for designing for bodily interactions is the interplay between Körper and Leib. One example provided by the authors is sensing a user’s heart rate and then “mak[ing] some inferences about a person’s feelings based on emotions, for example a feeling of calmness has rarely been associated with an excessive heart rate” (Mueller et al. 2018,

p. 5). Another design recommendation made by the authors is to support localized sensations in the body like force-feedback in a game control steering wheel. Localized sensations support the Leib side of design by moving the experience to the body as opposed to just seeing it on displays and hearing it in speakers. The authors also recommended using limitations of the Körper, such as having to rest after exercise, to make the Leib experience more interesting. An interactive bodily system should also be built to support “players in exploring the interplay between Körper and Leib and how it facilitates growing their understanding of it” (Mueller et al. 2018, p. 8). This can be done by creating moments when players return to their bodies, like closing their eyes. Another design consideration to shift focus back to the Leib is creating situations where there is a loss of bodily control. The authors suggest the ability to shift focus between Körper and Leib multiple times during the experience to make it more engaging. The last design recommendation the authors make is to create large physical disparities between input and output even though “this goes against common usability principles” (Mueller et al. 2018, p. 10). This study contributes to answering my research question by providing support for built in shifts between experience and reflection as shifts between Körper and Leib. Metaphor-based embodied interactions could be designed to have aspects of bodily feedback delivered if the interaction becomes too overwhelming, allowing for subtle and slower interactions with the same content while not fully engaged in the interaction. A limitation of this paper recognized by the authors is it does not investigate metaphors regarding Körper and Leib. Another limitation is that it deals with play and engagement rather than learning.

This section provides some answers to how effortful metaphor-based embodied interaction can affect the learning recall of abstract concepts that link to slowing down the pace of discovery. Lyons et al. (2012) noted heightened emotional engagement usually causes a narrowing of focus, but “if heightened emotional engagement is built gradually, this attentional narrowing can be avoided” (p. 4). Introducing a simple narrative element to the exertion gives the body the purpose it needs to connect its effort to some meaning. All these ideas support having longer term rather than one-time metaphor-based embodied interactions with content. Longer term interactions must consider ways to recreate initial shortcomings in usability to create the same gradual process of discovery. The process of discovery can be paired with a gradual rise in effort and emotional engagement, creating opportunities for new interactive ergodic literature and content pairings.

Also in this section, Malinverni et al. (2012) gave the participants time to play an interactive game with the slide before conducting the experiment to reduce the novelty of the interaction. However, the pre-test Malinverni et al. (2012) provided too much of a narrative for the participants and “could have had relevant effects by varying the attentional focus of participants and by modifying their selection of important information” (p. 66). Too much awareness of the context and the interaction took away from the exploratory instincts appearing in many of the studies of embodied interaction above. Harnessing and extending these exploratory instincts can be done by designing shortcomings in usability to create moments of reflection, and by using multiple metaphors to keep interactions novel. Mueller et al. (2018) argued for a continual shifting between Körper and Leib, exploring the possibilities and limitations of both to create more engaging and enjoyable gaming experiences. Learning abstract concepts through metaphor-based embodied interaction should require the same interruptive shifting for an understanding of the concept in the Körper and the Leib.

**Time for Reflection**

Shifting between Körper and Leib can also be seen as shifting between unreflective and reflective activity. Abrahamson et al. (2011) set out to answer the questions: "what forms should 'embodied learning' take? How should we theorize such learning? And what are the best design principles for creating technologies utilizing these theories?" (Abrahamson et al. 2011, p.1). The authors distinguish embodied interaction from other hands-on educational activities because it uses actions that are intrinsic to obtain information. The authors were concerned with conceptual ontogenesis in mathematics, meaning how higher-order ideas are developed. The authors designed a study for students to "discover, rehearse, and thus embody presymbolic dynamics pertaining to proportional transformation" (Abrahamson et al. 2011, p.3). The authors built the Mathematical Imagery Trainer (MIT) which measures the position of the user's hands while sitting at a desk. The MIT has a screen that turns red, yellow, or green depending on the user's hand positions in relation to the unknown proportion ratio being tested. The users are meant to maintain a green screen to show that the ratio on the grid is staying consistent in proportion increments. 22 students were recruited from a private K-8 school. Students participated in semi-structured interviews after using the MIT.

Abrahamson et al. (2011) found that all participants succeeded in finding ways to keep the screen green. The strategies the participants created were consistent with the mathematical concept of proportionality, so the authors argued the activity created teaching opportunities for those concepts. The authors wrote that "every student achieved a nontrivial level of understanding that emerged from considering common quantitative properties of all 'green' hand-pair locations" (Abrahamson et al. 2011, p.5). By observing where the hands are located, teachers could see students' thinking and can guide them in ways not available with traditional pencil and paper activities. The authors created the term "hook and shift" to describe how participants change their strategy when they "stumble upon the artifacts' embedded affordances that become revealed only through engaging with them, so that the students reconfigure their strategy in ways that co-opt these powerful affordances" (Abrahamson et al. 2011, p.6). In this activity, the students had no knowledge of what they were supposed to learn, but through holding the sensors that traced their hand movements and the feedback from the MIT screen, they were able to come to understand proportion first and then ratio later in the process. This study contributes to answering my research question by proving that abstract mathematical concepts can be learned without having any awareness of context and only using the process of learning to use the system while learning the concept. Future studies should attempt to pair the interaction with the content so that both are learned at the same time, and both contribute to the learning experience equally. A limitation of this study is that it did not investigate historical forms of physical performance to build into their system.

Stumbling upon the affordance of the interactive environment can be built into the design of the system. Antle et al. (2009b) set out to answer the research question "how does an embodied view of cognition (and interaction) inform the way we design interaction for hybrid physical and digital environments" (Antle et al. 2009b, p. 67). The authors conducted a study to test the Sound Maker environment to look for tacit and explicit knowledge as well as experiential benefits of embodied and non-embodied interaction. 20 pairs of adults and 20 pairs of children were recruited for the study. Participants completed structured exercises and then a composition exercise. This version of the Sound Maker (previously discussed above in Antle et al. 2008) had participants control four instruments of percussive sounds and four sound parameters through body movement in a room sized interactive environment. Participants worked in pairs to collaborate their body movements to change the sound parameters. For this study the authors were interested in "the potential benefits (and limitations) of incorporating embodied metaphors in the interactional layer of an augmented audio environment" (Antle et al. 2009b, p. 70). The authors hypothesized for the metaphor-based version that the adult participants would be able to explain and perform the system equally well, but the children would be able to perform better than explain the system.

The study found that adults correctly performed tasks in the metaphor-based version at a rate of 80% but correctly explained the task at a rate of 53%. Children were found to correctly perform the tasks in the metaphor-based version at a rate of 80% and correctly verbally explained the task at a rate of 47%. The authors also derived qualitative results from observational notes. The authors recommend importance placed on discoverability of mappings in interaction design and how it relates to user group and task order. The authors also recommend designers focus on the duplicity of mappings as some actions increase the likelihood of doing other actions. This is interesting when considering long term embodied interaction with the same content. Specific actions could be ordered to line up with the gradual increase in emotional engagement and advances in the narrative as mentioned above, leading to a choreographed effortful learning experience. I see future learning experiences to be active and structured in dynamic choreographed metaphor-based embodied interactions that are episodic and effortful, bringing the body into direct contact with the ideas. The authors also recommend feedback be immediate and easily perceivable especially if the participants are unfamiliar with input actions. As mentioned above, preserving unfamiliarity with input actions by adopting different metaphorical input methods for the same concepts may preserve the novelty of initial exploration and maintain engagement with the material. A limitation of this study is that it was based on learning the system, not the content.

Embodied interaction can be designed to not only blend feedback with everyday movements as seen above, but also with everyday self-regulation activities. Tancredi et al. (2022) set out to study a balance-based interface for math instruction called Balance Board Math (BBM). BBM offers learners "opportunities to both self-regulate through movement and to use their sense of balance as a resource for conceptual understanding" (Tancredi et al. 2022, p. 1). To use the BBM, a student shifts their balance on the board to dynamically change a generated graph on a display. The students can learn about amplitude, function, frequency, and other graph parameters. The authors note sensation seeking and self-regulating behaviors are similar in that they are "active attempts to meet one's sensory needs through activities such as rocking, pacing, and fidgeting that fall outside of the direct scope of the task at hand" (Tancredi et al. 2022, p. 2). The authors designed a study to answer research questions including how children engage in discovery-based learning and embodied self-regulation when using the BBM. The study recruited 6 participants from the 2nd to the 6th grade. The authors were searching for an equal number of students who identified as sensory-seeking and those who did not. The authors conducted semi-structured interviews on the BBM activities. For the activities, participants were invited to try out different motions on the board and instructed to find the green on the screen in as many tries as they liked. These sessions lasted an average length of 28 minutes. Between attempts participants were asked what made the screen turn green.

Tancredi et al. (2022) found that "through coordination of board and display, the children came to experience the graphs themselves multimodally" (Tancredi et al. 2022, p. 7). The participants were able to make better sense of printed graphs after the process because their experience of "being the graph" transferred over. Some participants were able to describe paper graphs using movement-based language showing that "the coordination developed between rocking and features of graphs became a resource for sense-making of static 2-dimensional representations" (Tancredi et al. 2022, p, 7). Many students used the board for self-regulatory rocking between attempts with the graphs, with the sensory seeking participants engaging in this behavior at a higher frequency. Because of the ability to continue rocking the board between attempts, the main activity and background activity converged, meaning "movement-for-regulation fluidly transformed into movement-as-thinking, intertwining and interacting rather than unfolding as separate processes" (Tancredi et al. 2022, p. 9). This study contributes to answering my research question by showing that everyday movements can be used to communicate abstract concepts. Imagine if learning content could be paired with actions we do every day, taking advantage of repeated behaviors to learn through metaphorically related concepts of our choosing. Conditioning and spatial learning could also be activated as many of our everyday motions are repeated in the same way in the same spaces. The authors suggest future research on the relationship between movement for regulation and exploration. I suggest future research on ubiquitous learning environments. The shortcomings of the study were only including six participants and having the participants all be young children.

This section made apparent having time for reflection is important for the learning recall of abstract concepts using metaphor-based embodied interaction. Abrahamson et al. (2011)'s study created "tension between unreflective orientation in a multimodal instrumented space, such as riding a bicycle or playing pong, and reflective mastery over the symbol-based re-description of this acquired competence" like many studies of embodied cognition in mathematics. Having the user feel like they both know what they are doing and not knowing what they are doing at the same time creates the gradual pace of discovery by allowing for reflection. This is the key point future studies should consider, how to extend the initial exploratory interaction with the interface and how to pair it with metaphorically related aspects of the learning content. Antle et al. (2009b) "suggest that the benefits of using an embodied metaphor in the interactional model may be limited to guiding and constraining initial input actions if perceivable confirmatory feedback is not readily provided" (p. 74). Time for reflection is not available to the user if there is not enough feedback to gauge what their bodily actions are causing. If the mapping is too obscure, "it is unlikely that it will be revealed by chance actions," leading to frustration of the learner and an unreflective search for the right interaction methods (Antle et al. 2009b, p. 74). Systems must be designed to include shortcomings in usability that extend the initial exploratory impulses but don't frustrate the user. Tancredi et al. (2022) showed us that self-regulation time, usually a time for reflection, can become part of the ongoing cognitive activity, creating opportunities for peripheral learning. Peripheral learning opportunities could be created in domestic environments to make interactive learning a non-stop process for those pursuing constant self-development.

**Learning**

Gelsomini et al. (2020) set out to investigate the pedagogical potential of an interactive immersive space for embodied learning called IMAGINE. IMAGINE stands for "Immersive Multimodal Ambient Gymnasium IN Education". IMAGINE uses wall and floor projections, lights, and auditory stimuli to respond to students' gestures tracked through the Microsoft Kinect. The teacher can customize the interactive educational experience to meet their students' needs. The authors organized an experimental study to answer the research question "can learning benefit from an immersive embodied approach compared to a traditional paper-based classroom approach?" (Gelsomini et al. 2020, p. 5). The authors identified a gap that most studies in this area have only investigated temporary learning impact and not long-term learning benefits. The learning sequence was structured around a four-phase process: challenge, initial thoughts, resources, and assessment. IMAGINE allows the interaction types of selection, classification, reordering, identification, and association. 70 participants were recruited for the study that were an average age of 6.94. The instructional topic for the study was the solar system. Since this was a long-term study, it was planned to be done over two months and use school tests for their quantitative analysis. The control group learned in the classroom using paper materials. The experimental group interacted with the solar system material in IMAGINE.

Gelsomini et al. (2020) found that students in the experimental group who used IMAGINE retained many more notions long-term than the control group who learned in the regular classroom. The groups were categorized in tertiles, with the first being participants who retained fewer concepts, the second tertile being the middle range, and the third tertile those who acquired more concepts. Specifically, "IMAGINE students retained an average of 3 notions more than classroom students in the first tertile, 1 notion more in the second tertile, and 9 notions more in the third tertile" (Gelsomini et al. 2020, p. 8). The authors found children with learning difficulties found the process of memorization easier using IMAGINE. The authors note the embodied immersive approach allowed participants to encode information in a way that allowed for embodied reflection, which allowed the material to enter long-term memory. This study contributes to answering my research question by being the only study to prove the long-term learning benefits of structured embodied interaction. A limitation of this study is that it was projection-based and did not offer tangible interactive opportunities. Another limitation is that the embodiment created through the interaction with IMAGINE was only at a low-medium level.

Learning and reflection are also connected by Marshall (2007) who presents an analytic framework for tangible interfaces to support learning. The author makes links to cognitive science and education to address the gap in previous research that only categorizes and describes existing tangible learning systems. Marshall (2007) notes that in past research links to increased engagement and reflection through physical action and digital effects have benefited tangible learning. Marshall (2007) also notes that the domains of chemistry and biology use tangible interfaces that "tend to be inherently spatial, either physically in the case of molecular models, or metaphorically in the representational systems typically used to represent them" (p. 2). The author discusses exploratory and expressive as two types of learning activities. One reason tangible interfaces are suitable for exploratory learning is that if the interface is natural or intuitive "minimal cognitive effort would be required to understand how the system works and more attention could be focused through the interface onto the underlying domain" (Marshall 2007, p. 3). One reason tangible interfaces are suitable for expressive learning is that by tracking the user's interactions with the tangible object, users can "construct expressive representations passively, while focusing on another task" (Marshall 2007, p. 4). The author states tangible systems can be created that combine expressive and exploratory activities to enhance learning benefits.

Marshall (2007) then discusses the notions of readiness-to-hand and presence-at-hand. Marshall (2007) notes that focusing too much on the readiness-to-hand features of most tangible interfaces neglects the attention of the tool or representation in the presence-at-hand notion. The author notes presence-at-hand is important because it can "involve periods of more objective reflection where knowledge is abstracted and conflicts are resolved" (Marshall 2007, p. 5). The author notes tangible interfaces that are too easy to use cause time for reflection, planning, and learning to be missed. The author notes intuitions about the benefits of tangibles should be replaced by empirical research. The framework laid out by Marshall (2007) recommends cycling between exploratory and expressive activities when designing tangible interfaces. The framework also recommends investigating combinations of abstract and concrete representations. The author's framework emphasizes the consideration of "a physical action leading to a digital effect or a digital action leading to a physical effect" which can lead to increased engagement and reflection. This study contributes to answering my research question by highlighting the importance of shifting between exploratory and expressive activities, like shifting between experience and reflection, and shifting between Körper and Leib. The shifting between mental states is vital to learning both the system and the content. A shortcoming of this study is that it is based on a review of the literature and does not include the testing of any of the ideas. As we are looking for Another shortcoming is it deals with tangible interactions and only briefly with embodied interactions. Future studies should be conducted testing Marshall's framework and investigating its applications to metaphor-based embodied interactions.

Investigating the abstract and concrete representations mentioned above, Chatain et al. (2023) sought to find out the impact of embodied concreteness on grounding and the impact of concreteness on learning outcomes. The paper defines embodied concreteness "as a form of concreteness that involves a high degree of embodiment, in a situated and relatable context" (Chatain et al. 2023, p. 3). Chatain et al. (2023) state that "concreteness" has different definitions in the mathematics field that span the following three categories: if an element can be touched, if it is more specific than general, and if it is more relatable than unfamiliar. "Grounding" as discussed in the paper refers to the process of mapping ideas to experiences that are personally meaningful. The abstract concept dealt with in this study was graph theory.

The design of the VR activity was a flow graph that used the water-flow metaphor schema represented through a pipe network. The participant was meant to increase the flow of water from the source to the sink to get a fountain to start pumping out water. Performing the study in VR was meant to achieve a higher degree of embodiment. The Chatain et al. (2023) study had three experimental conditions. The abstract condition involved solving the problem on paper with a graph representation that was geometrical, not the pipe and water network. In the manipulated concreteness condition the participants used the tablet with the pipe network representation to solve the problem but less embodiment because only fingers were used to interact with the tablet. In the embodied concreteness condition participants solved the problem with the pipe network representation in VR. 89 participants were recruited that were an average age of 20.6. The participants in the abstract and manipulated concreteness groups had 25 minutes to solve the problem while the participants in the embodied concreteness group had 30 because of the extra time to calibrate the VR. Once finished, participants took a three-minute break and then took a learning assessment test. Chatain et al. (2023) found that the manipulated concreteness and embodied concreteness conditions improved attention, confidence, and satisfaction for the participants. The researchers also noted that embodied concreteness improved perceived relevance and grounding because the abstract mathematical concepts were linked to real world applications. Chatain et al. (2023) found "no effect of the condition on learning outcomes with concrete representations" (p. 9).

This study contributes to answering my research question by showing the importance of real-world relatability of the interactions with content. Because the metaphorical water-flow problem and the action of turning spigots was relatable, it made the abstract graph theory more understandable. Chatain et al. (2023) mention a limitation of their study is they used different technologies for each of the concrete conditions they were testing. Chatain et al. (2023) also mention all their participants in the full study were mathematics students who were more familiar with some of the concepts than an average person. Chatain et al. (2023) also suggest a wider variety of bodies involved in future studies to expand the idea of embodiment. This is the only study reviewed to mention the need to use a wide variety of bodies with varying abilities in embodiment studies.

In this section we saw elements of metaphor-based embodied interactions that helped learning. Gelsomini et al. (2020) proved that long-term learning benefits are possible with only low to medium levels of embodiment. This is important as interactions don't require a high degree of commitment or effort, making the environment less stressful for students. A less stressful environment must be considered in the design of metaphor-based embodied interaction systems to maintain the initial exploratory instincts when encountering novel interaction methods. The IMAGE space allowed students to move their bodies around the environment to exert control over the learning material. Because the students' bodies were more involved in the lesson, embodied reflection on the material was possible in a way that it wasn't for the regular classroom students. Marshall (2007) connected to many of the ideas in other studies listed above about learning being in the exploration of the interface and the constant cycle between exploration and reflection. Chatain et al. (2023) showed that "concreteness can be defined as a property of the object only (concrete as specific), but also through the interaction of a learner with the object (concrete as tangible), or the mental model the learner has of the object (concrete as relatable)" (p. 10). The more relatable an embodied activity is, the more the content is committed to memory. Different stages of learning could be built that incorporate interaction with concepts on different levels of concreteness. In the future, interaction with the three types of concreteness could be structured in a simple narrative to be experienced through choreographed interaction just like textbooks and study guides are organized today.

**Discussion**

Now that we have finished examining the papers, we can tie together all our discoveries to attempt to answer how metaphor-based embodied interaction affects the learning recall of abstract concepts. In the first section above, The Unlimited Body and the Limited Object, we found that more metaphors are produced for concepts when using the whole body as opposed to using a tangible object (Bakker et al. 2009). Tangible artifacts allow for quicker learning of the system, but to the author's knowledge, no studies have been done to consider the long-term benefits of a slower learning process using embodied interaction. Lakoff and Johnson (1981) provide support for this future research when they state, "we feel that no metaphor can ever be comprehended or even adequately represented independently of its experiential basis" (p. 28). The experiential nature of embodied interaction allows for a deeper connection with the metaphor. A tangible artifact curbs the experiential basis of the metaphor, restraining the understanding of the metaphor, leading to a limited understanding of the abstract concept.

In the second section, Finding the Right Representation, we found the search for feedback from the system after a bodily movement was made was essential to the experience of learning. Dourish (2001) gets at this point when he wrote, "because we know that people don't just take things at face value but attempt to interrogate them for their meaning, we should provide some facilities so that they can do the same thing with interactive systems" (p. 49). Designing a system for this search for meaning in the initial exploratory stages of embodied interaction can be leveraged for learning by pairing it with the right unfolding of content. As you are discovering the system and the metaphors that activate it, you should also be engaging with introductory content that lays the foundation for the encoding of the entirety of the abstract concept. Once the exploratory stages of the learning the system are over and interaction with it has become second nature, new metaphors could be used to reintroduce novelty and spark the initial exploratory instincts with the system and the content.

In the third section, Remember the Effort, we saw more evidence for slowing down the process of discoverability through gradually building emotional engagement structured along a simple narrative (Lyons et al. 2012). This again can best be optimized when designing an interactive system by beginning to pair content with the initial exploratory process of discoverability. Instead of watching a how-to video, looking at an instruction manual, or participating in a free play session with the interface beforehand like in Malinverni et al. (2012), the abstract concept could be broken down into narrative stages of understanding and paired with each stage of interaction as the ease of interacting with the system becomes more natural. This would also result in the experimentation of multiple metaphorical methods of interaction, potentially deepening the learning of the concept. The third section also discussed Körper and Leib and designing for the back-and-forth interplay between the body as an object and the sensing/feeling body. Again, when designing for the initial process of discoverability, the user should be able to switch between seeing their body as the object and the way they are being made to sense/feel through their engagement with the activity.

The fourth section, Time for Reflection, showed that for the learning recall of abstract concepts, time to reflect is essential. To create a metaphor-based system that uses embodied interaction one must create a gradual pace of discovery where users switch back and forth between feeling comfortable and uncomfortable with the task (Abrahamson et al. 2011). Too quick of an orientation with the task, like interacting with tangible artifacts in Bakker et al. 2009, can cause the user to breeze by the important connection points between movement and activity. The process of discoverability must be designed and perfectly calibrated to create pauses between moments of certainty and uncertainty to make the foundational connections to let the learning of the abstract concept take hold.

The fifth and final section, Learning, provided empirical evidence for the benefits of long-term recall from embodied interaction. Students who used the IMAGINE space for embodied interaction learned more concepts than the paper and pencil student groups (Gelsomini et al. 2020). That this was possible with only low to medium levels of embodiment is of interest to our study because it shows that fancy systems with custom built artifacts and interaction methods are unnecessary for quality learning to take place. Chatain et al. (2023) showed that making the embodied interaction metaphor relatable helped the abstract concept to be learned. Combining both findings shows that there are opportunities for low-tech metaphor-based embodied interactive learning activities that people can develop on their own for their own purposes.

A major limitation found in most of the studies reviewed was using children as participants instead of adults. The inclusion of children limits the type and scope of abstract concepts that can be paired with metaphors. Adults also can pursue effortful interaction in a way that children would find too difficult, frustrating, or pointless. With some of the peripheral learning ideas linked to self-regulatory behaviors in the Tancredi et al. (2022) study, adults could structure their home environments as ubiquitous learning experiences. Pairing bodily engagement with content could turn lifelong learners into healthier adults and vice versa. Complicated abstract concepts could be made more accessible and become more quickly understood through using metaphor-based embodied interaction methods. More studies should be conducted with adult participants for these purposes.

Our research question of how metaphor-based embodied interaction affects the learning recall of abstract concepts can be answered in a few ways. Multiple metaphors being used to map to the same abstract concepts can help the learning of these concepts. Embodied interaction is better than tangible interaction to produce multiple metaphors. We can also answer the research question by slowing down and pairing abstract concept to the process of initial discoverability, leveraging the time to learn the system as the time to teach the content. Abstract concepts learned through metaphor-based embodied interaction can be presented through audio, VR, AR, interoceptively, co-located with tangible artifacts, or discretely represented separately from tangible artifacts. If the interface involves a lot of physical exertion, it is best to structure the process of that exertion along a simple narrative to maximize learning. Creating time for reflection in the process of interactivity, switching between Körper and Leib also maximizes the potential for learning abstract concepts. Providing relatable embodied metaphors to map abstract content to will also enhance the opportunities for learning. Future research should continue to find empirical evidence for the learning strategies suggested above. More studies with adults are needed to balance the studies in the area. More creative applications of these concepts like the Springboard developed by Antle et al. (2009a) should be developed and tested. Studies should also be done to investigate learning the system vs. learning the content when embodied interaction is used.

## Conclusion

Dourish (2001) writes of a trend in computing that “allows computation to be made ever more widely accessible to people without requiring extensive training, and to be more easily integrated into our daily lives by reducing the complexity of those interactions” (p. 14). We can interact with computers and get what we want out of them without having to be supremely skilled in coding or system functionalities. Dourish (2001) also writes of Heidegger’s distinction between ready-to-hand and present-at-hand and gives an example of a hammer. “When the hammer is present-at-hand, it is separate from me, while in the ready-to-hand case, my arm and the hammer feature as a single unit in my activity” (Dourish 2001, p. 139). We have opportunities for tangible and embodied interaction all around us in our daily lives. We can structure our own learning through engaging in metaphor-based low to medium level embodied interaction making it personal and relatable, using back and forth switching between reflective and non-reflective interaction, switching between Körper and Leib. The progress and prevalence of technology can level the playing field for accessing and understanding difficult concepts usually reserved for the ivory towers of universities and bringing them to individuals ready to explore their everyday environments for relevant metaphors to pair with content.

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