Do Gestural Interfaces Promote Thinking?
Embodied Interaction: Congruent Gestures and Direct Touch Promote Performance in Math

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ABSTRACT

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Can action support cognition? Can direct touch support performance? Embodied interaction involving digital devices is based on the theory of grounded cognition. Embodied interaction with gestural interfaces involves more of our senses than traditional (mouse-based) interfaces, and in particular includes direct touch and physical movement, which are believed to help retain the knowledge that is being acquired. There is growing evidence that spontaneous gestures affect thought and possibly learning. The author was interested to explore whether designed gestures (for gestural interfaces) affect thought. It was hypothesized that the use of congruent gestures helps construct better mental representations and mental operations to solve problems (Gestural Conceptual Mapping). There is also evidence that physical manipulation of objects can benefit cognition and learning; it was therefore also hypothesized that manipulating objects through direct touch on the screen supports performance. These hypotheses were addressed by observing children’s performance in arithmetic and numerical estimation. Arithmetic is a discrete task, and should be supported by discrete rather than continuous actions. Estimation is a continuous task, and should be supported by continuous rather than discrete actions. Children used either a gestural interface (multi-touch, e.g., iPad) or a traditional mouse interface. The actions either mapped congruently to the cognition (continuous action for estimation and discrete action for arithmetic), or not. If action
supports cognition, children who use continuous actions for estimation or discrete actions for addition should perform better than children for whom the action-cognition mapping is less congruent. In addition, if manipulating the objects by touching them directly on the screen could yield a better performance, children who use a touch interface should perform better than children who use a mouse interface. The results confirmed the predictions.
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CHAPTER 1: INTRODUCTION

According to theories of embodied cognition (Barsalou, 1999; Glenberg, 1997), concepts are primarily sensorimotor; thus, when speakers activate concepts in order to express meaning, they are presumably activating perceptual and motor information. Hostetter and Alibali (2008) claim that these sensorimotor representations that underlie speaking are the basis for speech-accompanying gestures. There is a growing body of research regarding the effect of spontaneous gestures on thought and their facilitation of the construction of mental representations and mental operations in problem solving (Alibali et al., 1999; Chu & Kita, 2011; Goldin-Meadow, 2009; Kessell & Tversky, 2010). There is also evidence from embodiment research that physical actions are compatible with mental states (Barsalou et al., 2003; Glenberg & Kaschak, 2002). The present study explores whether the compatibility of designed gestures (for gestural interfaces) could construct better mental representations and operations that facilitate performance. In order to support thinking, the gestures should be congruent with the learned concept and compatible with the mental representations and operations that are needed to solve the problems. This process is herein defined as Gestural Conceptual Mapping.

There is also a growing body of research based on embodied cognition theory that physical manipulation of objects supports thinking and learning (Bara et al., 2004; Glenberg et al., 2004; Ramini & Siegler, 2008). Studies about digital devices and learning provide evidence that incorporating the haptic channel yields better learning performance (Chan & Black, 2006; Han, Black, Paley, & Hallman, 2009; Jang, 2010).
The current study explores whether the use of gestural interfaces that incorporate direct touch could support cognition. Touch interfaces involve a higher level of direct manipulation of the objects and therefore could facilitate performance. The combination of congruent gestures and direct touch should yield a better construction of mental representations and operations of abstract concepts, thereby supporting performance.

The current studies explore the use of gestural interfaces (such as a multi-touch enabled computers, iPhones, and iPads) vs. traditional interfaces (such as monitor-keyboard-mouse) by young children for the purpose of better performance in math. The children performed two tasks. One of the tasks was counting and addition, which is a discrete procedure, and the other task was estimating numbers on a number line, which is a continuous procedure. The hypothesis is that children who use gestural interfaces that integrate a higher level of direct manipulation would outperform children who use traditional interfaces. Direct manipulation refers to the interaction of manipulating objects on the screen within various interfaces across different digital devices. The experiments compare the different levels of direct manipulation of the interfaces and shed light on how these affect thinking.

The direct manipulation is defined as following:

- Behavioral Mapping: Mapping the gesture to the cause and effect of the system, which results in better usability (Antle, 2007). The experiment controls for this.
- Gestural Conceptual Mapping: Mapping the gesture to the learned concept, which results in better performance. This is a new term defined by this researcher. It explores the compatibility between gestures and digital representations of the learned concepts. Gestures congruent with the learned concepts support thinking and possibly learning.
Children who use well-designed gestural interfaces that map the mental operations to congruent physical actions should perform better than children who use interfaces that do not map the mental operations to congruent physical actions.

• Direct Touch: Using a direct touch interface to perform these tasks results in better performance. The different levels of sensorimotor input (touch vs. mouse) affect performance. Children who use touch-based interface should outperform children who use mouse-based interface.

The author supports her theory with a body of research on embodiment, spontaneous gestures, gestural interfaces, and direct manipulation.
CHAPTER 2: THEORETICAL FRAMEWORK

Grounded Cognition and Embodied Interaction

*Action can play central roles in perception, acquisition, and thought*

Gibson and other researchers explored the relationship between perception and action and claimed that perception is for action; that the ability to perceive evolved from a need to interact with the world (Adolph, 1997; E. J. Gibson & Walk, 1960; J. J. Gibson, 1979). Gibson (1977) defined affordance theory, which states that the world is perceived in terms of not only object shapes and spatial relationships but also object possibilities for action. Tversky (in press) claims that action underlies perception. She suggests that the actions of organizing space into groups, hierarchies, orders, and the like create spatial patterns that are captured by the Gestalt laws of perception. Barsalou (2008), who has conducted extensive research in the field of grounded cognition and embodiment, claims that bodily rooted knowledge involves processes of perception that fundamentally affect conceptual thinking. Barsalou and colleagues (2003) found that there is a compatibility effect between one’s physical state and one’s mental state. For example, they found that participants who were asked to indicate liking something by pulling a lever towards them showed a faster response time than those who were asked to indicate liking by pushing the lever away. Another action-compatibility effect was demonstrated in a study by Glenberg and Kaschak (2002). They asked participants to read sentences that implied either motion away from the body (e.g., “close the drawer”) or motion toward the body (e.g., “open the drawer”). The results demonstrated an action-compatibility effect between the motion implied in a sentence and the motion of the response: participants
were faster to respond when their responses matched the direction of motion in the sentences. A study by Tucker and Ellis (1998) brought further evidence that perception leads to automatic planning of actions. They presented participants with visual photos of common graspable objects and asked them to decide whether the objects were upright or inverted. Participants demonstrated action compatibility effect with objects’ affordances. Neuroscience research regarding mirror neurons supports the claim that activating potential actions may be an automatic consequence of perception (Di Pellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti, 1992; Gallese & Goldman, 1998; M. Wilson & Knoblich, 2005).

Action compatibility effect was also demonstrated to be effective in learning. Schwartz and Martin (2006) found that when children used compatible actions to map their ideas in a learning task, they had better performance and could also transfer it to other domains. For example, children were given a bag containing candy and were asked to share it with four friends. In one group, children were asked to organize piles of candy into various groups (i.e., four equal groups). The other group of children was asked to solve the problem by drawing pictures of the candy to be shared. Children who learned through complementary actions were in a better position to solve problems of division in arithmetic. Physical manipulation with real objects has also been proven effective with children as young as preschool and kindergarten age (Siegler & Ramani, in press). In this study, children who played a simple linear numerical board game for four 15-minute sessions improved their numerical estimation proficiency and knowledge of numerical magnitude more than did children who played numerical board games that were not compatible with number representation. Some educational approaches, such as the
Montessori (1972) educational philosophy, suggest that physical movement and touch enhance learning. When children learn with their hands, they have more meaningful learning experiences.

Embodied interaction involving digital devices is based on the theory of and body of research on grounded cognition (embodiment) that cognition is affected by our interaction with the environment. Embodied interaction involves more of our senses than traditional (mouse-based) interfaces, and in particular includes touch and physical movement, which are believed to help retain the knowledge that is being acquired. In a study about including the haptic channel in a learning process with kinematics displays, Chan and Black (2006) found that the immediate sensorimotor feedback received through the hands allowed better learning for the students who were in the direct manipulation animation condition as compared to the students who were in the “passive” animation condition, who could not manipulate the objects on the screen. This interaction, with learners controlling the pace, speed, direction, and magnitude of the animation, enabled learners to actively engage and participate in the meaning-making journey and yielded better performance. In a study that incorporates the haptic channel as force feedback to learn how gears operate, Han, Black, Paley, and Hallman (2009) found that using three sensory modalities and incorporating tactile feedback helped participants efficiently learn how simple machines work. Furthermore, the haptic simulation group outperformed the other group not only in the immediate post-test, but also in the near transfer test, meaning that effectiveness of this embodied experience with haptic simulation was maintained during reading of instructional text. Another study providing evidence that using haptic simulation can benefit learning was done by Jang (2010). Participants who were medical
students were given either an animation or an active manipulation 3D virtual reality anatomical model of the inner ear. The manipulation group that was required to physically manipulate the model outperformed the visual group that was required only to watch the manipulation, suggesting that visual and motoric embodiment took place in supporting mental rotation and enhanced learning.

New technologies suggest new opportunities to include touch and physical movement, which can benefit learning, in contrast to the less direct, somewhat passive mode of interaction suggested by a mouse and keyboard. Antle’s (2007) research on tangible systems suggests that these interfaces are very powerful in engaging children in active learning. Dourish (2001) claims that rather than embedding fixed notions of meaning within technologies, embodied interaction is based on the understanding that users create and communicate meaning through their interaction with the system (and with each other, through the system). The use of the whole body can be seen as the more natural state of user interfaces. The current “traditional” computing arrangement of keyboard, mouse, and monitor goes against thousands of years of biology. Saffer (2009) suggested that human beings are physical creatures; we like to interact directly with objects. We’re simply wired this way. Interactive gestures allow users to interact naturally with digital objects, in a physical way, like we do with physical objects. Gestural interfaces provide a more hands-on experience and therefore could support cognition and create meaningful learning experiences by using a more direct manipulation of objects.

However, the author of this current paper believes that the design of gestural interfaces plays a critical role in their effect on thinking. Gestural interfaces could benefit cognition and learning only if the direct manipulation is designed to support that. In particular, I
believe that the gestures (actions) designed for gestural interfaces should be compatible with the mental operations and representations to support performance (Gestural Conceptual Mapping), such that one’s physical state is congruent with one’s mental state. Gestures are simulated actions that emerge from perceptual and motor simulations that underlie embodied language and mental imagery (Hostetter & Alibali, 2008). In the following chapter, I will review spontaneous gestures and their effect on thought, and then explain how they could be adopted to gestural interfaces for the purpose of affecting thinking.

Do Spontaneous Gestures Affect Thought?

**Gestures augment working memory and structure mental models**

There is growing body of research regarding spontaneous gestures and their effect on communication, working memory, learning, mental modeling, and reflection of thought.

Gestures help both speakers and listeners in communicating and comprehending. In a study about the role of gestures in speech, Iverson and Goldin-Meadow (2001) found that speakers gestured even when communicating with blind listeners, and that blind speakers gestured when speaking to other blind participants. This means that gestures serve a major function in speech. In a study about prevention of gestures, speakers who were directed to sit on their hands while communicating produced dysfluent speech (Morsella & Krauss, 2004).

Gestures also augment working memory. In a study regarding gestures and reducing cognitive load, Goldin-Meadow, Nusbaum, Kelly, and Wagner (2001) found that
gesturing improved participant performance in a dual task situation by offloading memory. They asked children and adults to explain how they would solve a math problem while simultaneously remembering a list of words. Participants remembered more words when they gestured than when they did not. The results suggest that gestures reduce cognitive load and augment working memory. In a study that explores the roles of gestures and diagrams in solving problems, Kessell and Tversky (2010) found that gestures create an embodied sketchpad, capturing memory and thought. In their study, during solution, problems with high spatial working memory demands elicited the most gestures or diagrams, suggesting that both serve to offload working memory. In contrast, during explanation, all problems reliably elicited gestures. The participants’ gestures were spatially congruent to the problem and augmented problem solving. The results suggest that gestures serve thought by augmenting working memory, and serve communication for both working memory and solution enactment.

Gestures reveal information about children’s developmental stage and could support learning. Goldin-Meadow (2009) claims that gesture plays a role in changing the child’s knowledge; children express knowledge in gestures that they could not express in speech. She claims that because gestures reflect thought and are an early marker of developmental change, it may be possible to use them diagnostically, which could be useful in learning and development. In a study on how gestures could promote math learning, Goldin-Meadow, Cook, and Mitchell (2009) found that requiring children to produce a particular set of gestures while learning the new concept of grouping strategy helped them better retain the knowledge they had gained during the math lesson, and helped them to solve more problems. Even gestures done by children as young as two to
four years old reveal information about their understanding of counting (Graham, 1999). In another study regarding counting and gestures, Carlson et al. (2007) proved that using gestures such as pointing increased both accuracy and speed in counting items. In addition, subjects who were not allowed to point tended to nod their heads, which was associated with greater accuracy.

Gestures are actions and can help people imagine mental operations and perform mental transformations. Schwartz and Black (1996) argued that spontaneous hand gestures are “physically instantiated mental models.” In a study about solving interlocking gear problems, they found that participants gestured the movement of the gears with their hands to help them imagine the correct direction of the gears, gradually learning to abstract the rule for that. In a study regarding motor processes and mental rotations, Wexler, Kosslyn, and Berthoz (1998) found that motor rotation that is compatible with mental rotation results in faster times and fewer errors in the imagery task than when the two rotations are incompatible. Also, the angle through which subjects rotated their mental images and the angle through which they rotated a joystick handle were correlated, but only if the directions of the two rotations were compatible. Chu and Kita (2011) found that gestures trigger mental images that help solve complex problems relating to spatial visualization. In a study that involved mental rotations and folding a paper, they found that when people have difficulty in solving spatial visualization problems, they spontaneously produce gestures to help them, and gestures indeed improved their performance. As subjects solve more problems, the spatial computation supported by gestures becomes internalized, and the gesture frequency decreases. Gestures may improve spatial visualization by helping a person keep track of an object in
the mind as it is rotated to a new position. They claim that since our hands are used so much in daily life to manipulate objects, gestures also may provide additional feedback and visual cues by simulating how an object would move if the hand were holding it. They conclude that gestures enhance performance on spatial visualization tasks by improving the internal computation of spatial transformations.

**Gestures reveal mental representations.** Emmorey, Tversky, and Taylor, (2000) found that gestures map spatial ideas onto a virtual space. For example, participants used a combined set of gestures to sketch a map in the air that included landmarks and paths. In a study about mental representations and gestures, Alibali et al. (1999) found that spontaneous gestures reveal important information about people’s mental representations of math-based problems. They based their hypothesis on a former body of research that showed that gestures provide a window into knowledge that is not readily expressed in speech. For example, it may be difficult to describe an irregular shape in speech but easy to depict the shape with a gesture. The authors hypothesized that such mental models might naturally lead to the production of spontaneous gestures, which iconically represent perceptual properties of the models. They compared gestures of subjects who solved discrete-change problems that focused on change over a series of steps (such as change in the number of books on each shelf of a six-shelf bookcase) to subjects who solved continuous-change problems that focused on change over a single, non-partitioned event (such as change in the amount of air flowing per minute into a hot air balloon over a 30-minute period). They showed that people spontaneously incorporated information about the manner of change into their representations of such problems, which illuminated their mental model representations.
If spontaneous gestures affect thought, could it be that choosing well-designed gestures (for gestural interface) could affect the mental operations of subjects and their performance? The dissertation explores the compatibility of gestures designed for gestural interfaces with the digital representations of the mathematical concepts of counting, addition and number-line estimation. By mapping the mental operations needed to solve the problem with physical actions (gestures), subjects could construct better mental operations and possibly representations of these abstract mathematical procedures.

Hostetter’s and Alibali’s (2008) theory of Gestures as Simulated Action (GSA) suggests that gestures emerge from perceptual and motor simulations that underlie embodied language and mental imagery. They provided evidence that gestures stem from spatial representations and mental images, and proposed the gestures-as-simulated-action framework to explain how gestures might arise from an embodied cognitive system. If gestures are simulated actions that result from spatial representation and mental imagery, it is very likely that asking users to perform one gesture vs. another could affect users’ mental operations and representations to solve the problem in different ways. The author of this current paper believes that well-designed gestural interfaces that incorporate a higher level of direct manipulation (Gestural Conceptual Mapping) could allow for the construction of better mental operations and representations, and essentially better performance.

In the following section I will review the connection between spontaneous gestures and gestural interfaces.
Gestural Interfaces and Spontaneous Gestures

*If spontaneous gestures affect thought, could well-designed gestures (for gestural interface) affect performance?*

In today’s world, innovative interfaces surround us. As educators, HCI designers, and cognitive psychologists, we have the responsibility to explore the advantages and disadvantages of these novel interfaces for cognition and educational use. The author’s aim is to explore more naturalistic interfaces for cognition and educational purposes.

Gestural interfaces are also known as “natural user interfaces” and include two types; touch interfaces and free-form interfaces. Touch use interfaces require the user to touch the device directly, and it could be based on a point of single touch (e.g., SMART Board) or multi-touch (e.g., SMART table / iPhone / iPad / Surface). Free-form gestural interfaces do not require the user to touch or handle the device directly (e.g., Microsoft Kinect). The mechanics of touch screens and gestural controllers have at least three general parts: a sensor, a comparator, and an actuator. The current studies focus on embodied interaction through multi-touch interfaces (HP Multi-touch laptop, iPhone, iPad) vs. traditional computer interfaces interaction.

Saffer (2009) defines gesture for a gestural interface as any physical movement that a digital system can sense and respond to without the aid of a traditional pointing device, such as a mouse or stylus. A wave, a head nod, a touch, a toe tap, or even a raised eyebrow can be a gesture.
Gestures for gestural interfaces are done on objects. One has to differentiate between gestures and gestures that are done on objects. In the case of designing gestures for gestural interfaces, these gestures are done while manipulating objects on the screen. Particularly, these gestures are actions that manipulate objects on a screen. In this case the congruency principle of effective graphics to support the learned concept, should be also applied, and the gestures should be mapped to the graphic (digital) representations. This supports the mental operations that are performed to solve a problem (see more details in Gestural Conceptual Mapping and Performance section).

There should be mapping both of the graphic representation to the learned concept, which is external manipulation, and mapping of the body movements (gestures) to support internalization of the learned concept. The theory of embodiment is that one has knowledge in his body movements that supports higher order cognitive processes. It is believed that these body movements emerge from the pre-motor cortex area, where planning takes place. This planning supports the internalizations of a concept. The current studies involve body movements on objects. These gestures are preformed for oneself (support internalizations of concepts), not for communication, and they should be congruent with external objects (in this case, with the graphic representation).

Spontaneous gestures that we are using as a part of our everyday language are being adopted by gestural interface designers in order to incorporate more natural and intuitive interactions. There are four types of spontaneous gestures: deictic, iconic (show relations), metaphoric (more abstract) and beat (discourse). Deictic gesture, such as pointing, is typically used for gestural interfaces. Iconic and metaphoric types of gesture
are also very common to adopt for gestural interfaces, and usually indicate a more complex interaction. Using a familiar gesture (from everyday language) to interact with interfaces could ease the cognitive load of the user. It creates a more transparent interface and natural interaction with the computer. Thus, it is logical to assume that well-designed gestural interfaces that integrate a higher level of direct manipulation could yield better performance. The properties of direct manipulation explored in the current study are: 1) Mapping of gestures (actions) to mental operations and representations with the learned concept; the author defines this as Gestural Conceptual Mapping and bases her theory on action compatibility effect studies and spontaneous gestures research, and 2) Adding the direct touch mode of interaction, based on studies of physical manipulation with objects.

I differentiate between the mapping of gestures for usability purpose (Behavioral Mapping) and mapping of gestures for performance and learning purpose (Gestural Conceptual Mapping) and am interested in the latter. In the following section, the differences between these two different mappings are described and presented as properties of direct manipulation.

**Direct Manipulation**

Direct manipulation has been defined by Shneiderman (1983) as the ability to manipulate digital objects on a screen without the use of command-line commands (e.g., dragging a file to a trash can instead of typing “del”). It allows a user to interact with a visualization corresponding to the real-world analogue it follows. It avoids the barrier of having to translate ideas into commands meaningful to a computer by building a graphical user interface that is semantically in line with the representation. The criteria for direct
manipulation are the continuous representation of objects of interest and the fast, incremental, undoable actions, which have an immediate visual impact on the object itself. The goal is to allow the user to directly interact with the object.

Direct manipulation in the HCI field has been consistently changing over the past few years. This is a result of a boom in the development of new technologies and innovative interfaces, which have taken direct manipulation to another level. This is especially true for touch-screen and free-form gestural interfaces that do not use external control devices to manipulate objects on the screen. Instead, they utilize the user’s own body to manipulate objects on a screen, changing the level of direct manipulation.

Different from Shneiderman’s initial definition of direct manipulation, that mainly refers to the graphic representation properties as being limited by conventional mouse/keyboard interaction, the author of this paper attempts to add additional properties of direct manipulation, that include mappings of the user’s actions to the graphic representation within more naturalistically innovative interfaces; movement that is more representational of the action in the real world. This minimizes the distance between the metaphors created by the interface and the actual action one attempts to represent, in the said interface metaphor. For example, the action of one dragging a document into the garbage bin on a desktop user interface using a mouse based interface vs. a user mimicking the real world gesture of taking a piece of paper crumpling it into a ball and throwing into a physical garbage bin (something made possible via the technology of the Kinect System). This attempt refers to interfaces that involve more of our direct body interaction, rather
than including external devices (to manipulate the objects) as being more direct. Figure 1 represents a trend of the levels of direct manipulation of interfaces in a virtual environment, according to the new definition, which is based on the embodiment theory. It’s important to clarify that this graph is not an accurate analysis and the levels of direct manipulation across interfaces cannot be entirely generalized for each task and scenario (see details in the discussion section). However, Figure 1 is included in order to highlight the trend of body involvement within gestural interfaces, and how these interfaces could be more direct in that sense.

The graph starts with low levels of keyboard and mouse interface, and continue with a higher level of direct manipulation, with generic game controllers and then generic game controllers with force feedback interfaces. They then move to the scale of a tablet and stylus touch screen, up in scale to finger touch-screen gestural interfaces (e.g., SMART board), multi-touch screen gestural interfaces (e.g., iPhone, iPad, Surface, SMARTtable), action specialized game controls with force feedback interfaces (e.g., racing car games), free-form gestural interfaces (e.g., Wii), camera-driven free-form gestural interface (e.g., EyeToy), and finally, to immersive reality (e.g., Microsoft Kinect, Xbox), where we can make gestures in space to control objects on screen. At the higher levels, enhanced direct manipulation incorporates the embodied interaction. Interfaces that allow enhanced direct manipulation are usually more intuitive for the user, and therefore could reduce cognitive load and allow better performance. The current studies explore different levels of direct manipulation utilized by various interfaces for the benefit of cognition. The author defines three properties of direct manipulation that are critical aspects of a gestural
interface design, especially when it involves performance goals: Behavioral Mapping, Gestural Conceptual Mapping, and the Direct-Touch Input.

![Diagram showing the level of direct manipulation of interfaces in virtual environment](image)

**Figure 1.** Level of direct manipulation of interfaces in virtual environment

**Behavioral Mapping and usability**

Dourish (2001) and other researchers and designers of human-computer interaction have been exploring the field of embodied interaction for the past few years. They suggest that well-designed natural interfaces could possibly be more intuitive for users and easier than traditional interfaces for certain tasks. Saffer (2009) explored gestural interfaces and suggested that the most natural designs are those that match the behavior of the system to the gesture humans might already use to enable that behavior. Some examples of this are putting your hands under a sink to turn the water on, pushing a button to turn something
on and off, and turning to the left to make your on-screen avatar turn to the left. These
movements or gestures are seemingly effortless, intuitive, and natural for the user
(although their functionality requires significant effort on the part of the designer). Antle
(2007) defined this as behavioral mapping, the mapping between cause and effect, where
the user has better control over the interaction. This is one of the properties of direct
manipulation that the current studies explore. It is mainly related to usability, and it is
defined as the control the user has over the interaction with the interface. An interface
that is transparent and easy to use has well-designed behavioral mapping. When the user
interacts with the interface he does not think of how to manipulate the features of the
interface (buttons, menus, etc.) on the screen, since it is “transparent.” He can focus only
on the content. Fukasawa (2006) claims that the best designs are those that “dissolve in
behavior.”

Usability of interfaces for children’s comprehension has been explored in the past few
years by HCI researchers, and it has generally been found that when designing for
children there are few major aspects of usability that are different then when designing
for adults. Shneiderman (1998) found that complexity, familiarity, and concreteness—in
addition to “good design” factors of consistency, feedback, closure, no errors, control,
minimal cognitive load, reversal flexibility, and multi-layers—are important for
children’s comprehension of an interface. Play, aesthetics, and content were also found to
be valuable. In addition, children’s fine motor skills are one of the main developmental
aspects that need to be considered in behavioral mapping. Gallahue and Ozmun (2002)
found that the use of a mouse to interact with interface features, and the tracking of the
cursor on the screen, are visual and motor capabilities that are difficult for young
children. Visual-motor coordination, the ability to track and make judgments about how to intercept objects, is also improved throughout childhood. By age five or six, children can track objects moving on a horizontal plane, and, by eight or nine, they can track objects moving in an arc.

Strommen (1993b) developed a model for HCI for children that include the use of control devices for HCI in regard to the developmental stage of children to operate these (e.g., mouse, joystick). The model is based on the theory of cognitive development of acquisition of knowledge. This means that young children will have a hard time operating a mouse to control the cursor on the screen, because of both the lack of experience and the shortage of working memory to store the information. These require activation of knowledge from long-term memory and working memory. In order to explore the cognitive demands of the children, Strommen and colleagues studied the ease of use of different pointing devices, and the ease of use of pointing a cursor to the screen, by three years old (Revelle & Strommen, 1990; Strommen, 1993a; Strommen, Razavi, & Medoff, 1992). They found that touch screen was easiest to use, followed by light pen, trackball, mouse, joystick, and finally arrow keys. Stromman’s et al. study refers to usability and behavioral mapping. It focuses on the control that the user has on the interaction with the interface within different digital devices. In the next section I will define what Gestural Conceptual Mapping means. This section will focus on the importance of designing congruent gestures for the purpose of improved content comprehension.

**Gestural Conceptual Mapping and performance**

Marshall (2007) suggests that there is a gap in the existing research on tangible interfaces and learning. He claims that there is no research on how users abstract the underlying
rules or laws of a domain, and how different levels of representation become integrated within the design. The gap, theoretically speaking, is about how the structure of the learning domain can be represented by the interface. This dissertation study explores the gap described by Marshall, and defines it as Gestural Conceptual Mapping. The term Gestural Conceptual Mapping is used to convey the mapping of the representations of the physical embodied metaphor (the gesture) onto the digital representation of the learned domain, supporting the mental operations allowing problem solving. Gestural Conceptual Mapping is one of three properties of direct manipulation. A first condition to mapping gestures (actions) to the learned concept is mapping the digital representations (visuals) to the learned concept.

Tversky et al. (2002) define the term Congruence Principle for effective graphics: the structure and content of the external representation should correspond to the desired structure and content of the internal representation. This means that graphics externalize internal knowledge, benefiting the individual’s mind by reducing the burden on memory and processing by offloading. This would be the digital visual representation of learned concepts, which are mapped to internal learned concept representations. An example from the current studies would be the visual (digital) representation of virtual blocks in the form of adding blocks in a pile (one on top of the other), in a discrete manner. This external visual representation of building a tower of blocks is compatible with the internal representation of the discrete counting procedure of adding one block at a time.

The current studies add the gestural external representation aspect (Gestural Conceptual Mapping), and it is hypothesized that mapping the gesture to the learned concept, and having compatibility between the representations of gestures (actions) to the digital
representation, will support the compatibility of the internal representation of the user. For example, tapping with a finger on a block or clicking with a mouse on a block to count and add up is a gesture (action) that is compatible with the discrete representation of counting. By contrast, sliding the finger vertically over a series of blocks or dragging a mouse on a series of blocks to count them are continuous movements and do not mimic the discrete procedure of counting.

Tversky (in press) claims that visualizations are the permanent traces of gestures; both embody and are embodied. Like gesture, visualizations use position, form, and action in space to convey meanings. The current studies explore the compatibility of the learned concept “visualization” (digital representation) with the physical representation of the gesture, and with the internal representation of the learned concept. For example, using congruent gestures with the learned concept could help a student construct better mental operations of the mathematical procedures needed to solve the problem.

The Congruence Principle of the mapping of graphic representation to the learned concept is critical to supporting learning and mental imaging and is a pre-condition to the Gestural Conceptual Mapping that the current studies explore. Not only should the graphic representation be compatible with the learned concept, but the gesture (action) should be compatible with the learned concept as well. This is herein defined as Gestural Conceptual Mapping. The gesture that is an external representation (embodied metaphor) of the learned concept should support the internal (imagined) representation of the learned concept. The mental operations should be mapped to the physical actions (gestures).
The representation of content should be an integral part of the interface, and the interaction should be meaningful for learning. This means that both the digital representation of the content and the gestures need to be compatible with the learned concept. Therefore, there must be compatibility between the external representation of the content and the internal representation that the user constructs. This compatibility supports the user’s mental imaging and allows for the construction of better mental representations and operations. In order to achieve this compatibility, designers should find the compatible embodied metaphor that would best illustrate the learned concept. The embodied metaphor is the type of gesture chosen by the designer to manipulate the educational content on the screen.

Metaphors and Embodied Metaphors

Lakoff and Johnson (1981) claim that metaphor plays an extensive role in the way we function, the way we conceptualize our experience, and the way we speak. They were mainly concerned about how people understand their experiences and view language as providing data that can lead to general principles of understanding. Metaphors allow us to understand one domain of experience in terms of another. Metaphors are conceptual in nature and are among our principal vehicles for understanding. Metaphors are based on simple physical concepts—up-down, in-out, object, substance, etc.—that are as basic as anything in our conceptual system. Without them we could not reason, communicate, nor function in the world, but they are not in themselves very rich. An example of a direct metaphor is “I’m up” for “I’m happy,” or “down” for depressed. Embodied metaphors are those that involve metaphorical gestures such as making a “v” shape with two fingers.
as a gesture for communicating “victory,” or using the thumb to communicate “well
done.”

Gestural Conceptual Mapping involves embodied metaphors of gestures that are mapped
to the learned concept. As an example from the current study, the gesture of tapping on a
touch-screen when selecting a block with your finger in order to count and add up (virtual
blocks in a pile) is conceptually mapped to the concept of discrete counting and adding.
This is a metaphorical gesture, since it is using the metaphor of the experience of adding
up physical blocks in a discrete manner and illustrates a constant tempo of discrete
procedure that goes up. If we use another gesture for the same task, such as sliding our
finger up the blocks, it will not be mapped conceptually to the concept of discrete
counting. This is because the sliding up gesture is based on a metaphor that adds up
something that is continuous and not discrete, such as filling up a glass of water. It does
not map the concept of discrete counting and therefore does not properly support the
internal operation; on the contrary, it is a misleading metaphor to the learned concept of
counting blocks.

Another example of well-designed Gestural Conceptual Mapping is an embodied
metaphor, such as a gesture of sliding the finger horizontally on a number line to estimate
a number. This kind of gesture illustrates the internal representation of continuous
procedure and supports the magnitude concept of a number line. By using well-designed
embodied metaphors (gestures) to support internal representation of learned concepts, the
user’s internal representations of the learned concepts are grounded by the appropriated
physical actions.
Metaphors are symbolic representations of concepts. DeLoache et al. (2003) suggest that symbolic understanding requires dual representation of the symbol (every symbolic artifact is also an object in and itself), and that young children may have difficulty simultaneously holding in their mind two aspects of a given symbolic object. The younger the child, the more he or she can only focus on one dimension, usually the more concrete one. Embodied metaphors are concrete since they are based on physical movement and the sensor motor channel. Children under the age of seven or eight have problems with most standard metaphor interpretation tasks, but they show understanding of the physical and the action-resemblance metaphor, provided some facilitation is introduced (Vosniadou, 1987). The author of this current paper believes that young children can benefit from concrete, physical metaphors, especially when these are mapped to their mental operations. When embodied metaphors are used in an interface, and are mapped conceptually to the learned concept, they support the metaphor of the digital representation (such as building with blocks) and synchronize the mental representation of the procedural concept (counting and adding up) to the interaction with the body. The physical movement of the body (embodied metaphor) supports the internal operations of the learned concept and makes the experience more concrete. Therefore, young children can benefit from well-designed gestural interfaces that include embodied metaphors (gestures) that are mapped to the learned concept.

**Direct-Touch Input and performance**

A third property of direct manipulation explored in the current studies is the direct touch input. Research has shown that physical manipulation can enhance the processing of abstract content and the comprehension of learned concepts. Some studies show the
positive influence of physical manipulation in learning and memory. In a study that explores Direct Manipulation Animation (DMA) incorporating the haptic channel in the learning process (where learners not only can visualize the information but also interact with it through their hand controls), Chan and Black (2006) found that the immediate sensorimotor feedback subjects received from their hand motions was transferred to working memory for further processing, which benefited the learning process. Glenberg, Gutierrez, Levin, Japuntich, and Kaschak (2004) found that experiences of physical manipulation become grounding for young children’s reading comprehension. First- and second-graders were asked to manipulate physical toys to correspond with a sentence while they were reading a story. This helped children to index words and phrases to real objects and resulted in better understanding of the story. A study by Bara et al. (2004) regarding alphabetical learning with children aged five showed that haptic exploration helped children’s abilities to link the orthographic representations of the letters with the phonological representation of the corresponding sounds (which could not be done with only visual and auditory training). Research on physical manipulations and mathematics learning (Ramini & Siegler, 2008; Siegler & Ramini, in press) showed the benefit of sensorimotor input. These studies explored whether playing a number of board games benefited estimation of numbers on a number line. In both studies, low-income children produced substantial improvements in number-line estimation, which seemed to be due to their increasing use of linear representations of numerical magnitudes. Numerical board games helped children produce the kinesthetic cues by physically moving the tokens in a linear (vs. circular way, which creates perceptual grounding to be linked to abstract symbols (numbers) and also helps children better comprehend the linear number line and
the concept of magnitude. According to Laski and Siegler (2007), the linear relationships between numerical magnitudes and these kinesthetic, auditory, visuospatial, and temporal cues provide a broadly based, multi-model foundation for a linear representation of numerical magnitudes.

Based on this body of research, it appears that gestural interfaces that incorporate the haptic aspect of touching the interface and manipulating the objects, by using higher level of sensorimotor input, could benefit users’ comprehension of learned concepts. In the current studies, it is hypothesized that by touching the objects on a screen directly with their finger/fingers, participants help themselves process abstract content and build internal representations that are more accurate. Touching the objects on a screen directly, with our body, rather than having a control device such as mouse or even stylus, could enhance the experience and make the learning experience more direct and integrated with the content. It is a more concrete experience that could support young children’s internal representations of learned concepts.

I believe that the combination of the three direct manipulation properties—behavioral mapping, gestural conceptual mapping, and the direct-touch input are critical for the support of thinking. Well-designed gestural interfaces that incorporate a higher level of direct manipulation should yield better performance.
CHAPTER 3: THE PRELIMINARY STUDY

Participants and Design

Ten four- to five-year-old children with middle-income SES were asked to perform two math tasks utilizing different interfaces. Since it was an exploratory pilot study, the design was both within and between subjects.

Method

Two learning math tasks with virtual manipulatives were chosen to examine the effect of high direct manipulation provided by gestural interfaces (HP multi-touch laptop and iPhone) compared to traditional interfaces (mouse interface). The tasks were a counting and addition task, and a tangram puzzle-solving task. For measurements, accuracy and time on task were recorded. The direct manipulation was examined in both tasks and included two variables:

• Gestural Conceptual Mapping: Mapping the gesture to the learned concept, which results in better performance. This is a new term defined by this researcher. It explores the compatibility between gestures and digital representations of the learned concepts. Gestures congruent with the learned concepts support thinking and possibly learning (e.g., rotating shape with finger rotations, which is compatible with mental rotation, vs. rotating shape by tapping with finger on shape, which is not compatible with a mental rotation procedure). Children who use well-designed gestural interfaces that map the mental operations to congruent physical actions should perform better than children who use interfaces that do not map the mental operations to congruent physical actions.
• Direct-Touch Input: Adding the direct-touch to perform these tasks results in better performance. The different levels of sensorimotor input (touch vs. mouse) affect performance. Children who use touch-based interface should outperform children who use mouse-based interface.

Children were given a pre-test to assess ability and a post-test to assess transfer of knowledge in counting, addition, and transformation of shapes. In all interfaces the experimenter demonstrated the use of one question and allowed one practice question. Parents filled out a one-page questionnaire regarding their child’s age, former experience with the devices, and knowledge of the domains.

Task 1: Counting and Addition

Children were required to solve five additions problems by working on a virtual manipulatives interface, with numbers from 1 to 10, such as 3+3, 4+1, 5+2. Two variables were examined: the Direct-Touch variable and the Gestural Conceptual Mapping variable.

The first variable compared the use of Direct-Touch (multi-touch interface) vs. Non-Direct-Touch (mouse interface). Children in the Direct-Touch condition had to tap with their finger on a multi-touch interface to fill in digital blocks in a bar chart and solve addition problems. Children in the Mouse condition had to fill in the digital blocks and solve addition problems by clicking with a mouse via a traditional interface (see Figures 2 and 3).

The second variable compared an interface that integrated Gestural Conceptual Mapping vs. an interface that did not. In the Gestural Conceptual Mapping condition children were
required to solve the addition problems by either tapping with their finger (in touch interface) or clicking (in mouse interface) on each individual block to highlight its color. This interaction with the interface mapped their gestures/actions to the discrete process of counting. Their gestures were congruent with the learned concept of counting and adding individual blocks. The children in the Gestural Non-Conceptual Mapping condition were required to solve the addition problems by either tapping with their finger (in touch interface) or clicking (in mouse interface) only on the number symbol that was placed under each blocks column. Then the computer highlighted the blocks colors for the children automatically. This interaction was not mapped to the learned concept of manipulating the objects in a discrete manner. The gestures required for this interaction were not congruent with the procedure of counting and adding each individual block. The procedure of counting is a discrete one, and therefore the external representation of mapping the gesture of the user to click (or tap) on each block is compatible with the internal mental representation for counting. This could allow for a better construction of mental operations of counting and adding up (rather than having the blocks highlighted automatically, which is not conceptually mapped to the concept of counting).

*Figure 2.* Direct-Touch condition; a multi-touch interface to perform the addition task
Task 2: Tangram puzzle solving

Children were required to solve one online tangram puzzle. Two variables were examined: the Direct-Touch variable and the Gestural Conceptual Mapping variable.

The first variable compared the use of direct-touch vs. non-direct-touch, such as solving a tangram puzzle on a multi-touch interface (iPhone) vs. solving a tangram utilizing a traditional interface with monitor and mouse (see Figures 4 and 5).

The second variable compared the use of an interface that integrated Gestural Conceptual Mapping vs. an interface that did not. For example, the tangram on the iPhone had two
applications; in the Gestural Conceptual Mapping condition, the gesture of the user was mapped to the learned concept. The user could rotate the tangram shapes with his fingers, thus the user created the turning of the digital object. Representing and supporting with his fingers rotation the mental rotation needed to solve the puzzle. The other application on the iPhone that represented the Gestural Non-Conceptual Mapping did not map the gestures to the learned concept. The user tapped on the middle of the shape in order to rotate it. Both interfaces were haptic (iPhone), but one allowed an interaction with congruent gestures (rotating) to the mental operations, and the other involved non-congruent gestures (tapping). The compatibility of the external representation (congruent gesture) of rotating the shape with the fingers with the internal representation of mental rotation should support the transformation of shapes needed to solve a tangram.

![Image of a smartphone with a tangram puzzle being solved](image)

**Figure 4.** Direct-Touch condition; a multi-touch interface (iPhone) to perform the Tangram puzzle task
Results

*Less time on task and better accuracy with touch interfaces in addition task*

In the addition task, children who interacted with the touch interface spent less time on task than children who interacted with the mouse interface. For the children in the Direct-Touch condition the average time for an answer was 7 seconds, compared to 15 seconds for the children in the Mouse condition (see Figure 6).

With regard to accuracy, in the addition task, children who were in the Direct-Touch condition were more accurate and had 93% correct answers, compared to children in the
Mouse condition, who had only 66% correct answers. Thus, children who used touch interface outperformed children who used mouse interface (see Figure 6).

With regard to strategy use, although strategies were only partially recorded, the experimenter observed that in the addition task, children in the Direct-Touch condition used the advanced “count on” strategy more times and used their fingers less for counting. Most of the children who used the mouse needed to also count and add the blocks using their fingers (see Figure 3).

_Better accuracy with touch interfaces in tangram task_

All children in the Direct-Touch condition (iPhone) succeeded in matching between one and seven shapes in the tangram solving task, resulting in 38% of their answers being correct, in contrast to the Mouse condition (mouse interface), where only two children managed to match one shape, with only 4.7% of their answers being correct. Children who used touch interface outperformed children who used mouse interface (see Figure 7). However, this result seems to be mainly due to usability issues (i.e., behavioral mapping), which will be discussed later.

In the tangram task, children who interacted with the touch interface (iPhone) spent more time on task than children who interacted with the mouse interface. For the children in the Direct-Touch condition the average time for solving the tangram was six minutes, compared to five minutes for the children in the Mouse condition (see Figure 7). The reasoning is further discussed later.
Better accuracy with congruent gestures in tangram task

Solving for the tangram task, in the Gestural Conceptual Mapping condition, 38% of the participants’ answers were correct, compared to 21% correct answers in the Gestural Non-Conceptual Mapping condition. Children who rotated the shapes with their fingers (congruent gesture) performed better than children who tapped in the middle of the shapes (incongruent gesture) in order to rotate them. Children who used congruent gestures outperformed children who used incongruent gestures.

In solving for the addition task, the results were different. The percentage of correct answers was higher with the Gestural Non-Conceptual Mapping condition (85%) than in the Gestural Conceptual Mapping condition (66%). However, both conditions were conducted on a traditional interface using a mouse and not a gestural interface (see Figure 6). The interaction with the mouse was either congruent to the learned concept or not.

Discussion

The pilot study was exploratory and resulted in five major findings. First, confirming the hypothesis, using touch interfaces compared to mouse interfaces supported performance in accuracy. Across both tasks, children who were in the Direct-Touch condition outperformed children who were in the Mouse Condition.

The second finding was that, in solving the tangram task using the iPhone, children who used congruent gestures outperformed children who did not use congruent gestures. This confirmed the hypothesis that Gestural Conceptual Mapping for gestural interfaces promotes performance. However, this was not the case for the addition task, perhaps
because the Gestural Conceptual Mapping was explored using mouse interfaces. Perhaps using congruent actions to the learned concept is more beneficial to cognition with gestural interfaces and not with traditional (mouse-based) interfaces that are less direct. Therefore, the researcher concluded that for the dissertation study, four conditions would be explored across both tasks. Here, the fourth condition was explored only in one of the tasks.

With regard to time spent on task when solving for the addition task, children who interacted with touch interfaces spent less time than children who interacted with mouse interfaces. It appears that the touch interface allowed a better flow of interaction. This is a behavioral mapping property that allows children better control of the interaction, and reduces the mental effort required by working memory. It supports the findings of Revelle and Strommen (1990) with respect to the ease of use of a touch screen for younger children, compared to a mouse-based interface. This however, was not true for the tangram task, where children in the Direct-Touch condition spent more time on task. The experimenter believes that this finding might be due to the fact that children in the Mouse condition did not match as many shapes of the puzzle as children in the Direct-Touch channel condition and therefore spent less time on task working with the mouse interface. Children had usability problems rotating the shapes with the mouse (behavioral mapping), which is most likely attributable to the development of their fine motor skills. Therefore, the researcher concluded that a better task should be designed for the dissertation study that would not yield a usability issue. In addition, in order to better control for behavioral mapping, the researcher would conduct two usability tests to
minimize the effect of usability issues. And lastly, children’s age would be modified to match their fine motor skills to the task at hand.

Another interesting finding was regarding strategy use. Although strategies were only partially recorded, the experimenter observed that when solving for the addition task, children who used the touch interface seemed to use the advanced “count on” strategy more times than children who used the mouse interface (who used their fingers more for counting). Ginsburg (1989) presents eight different strategies that young children use for counting. One of the strategies is the gesture of using their fingers to represent what is not present. Ginsburg claims that for some children, fingers are virtually inseparable from numbers. The use of a multi-touch screen for counting incorporates the natural use of fingers for counting and addition. Children in the touch interface condition used the “count on” strategy (e.g., 5+2 : “1, 2, 3, 4, 5, 6, 7. Seven”), which is a more developed strategy to add up. By contrast, when they used the mouse to count and add, they did not “count on,” but rather counted the numbers first and then added them up a third time (e.g., 5+2 : “1, 2, 3, 4, 5.” “1, 2.” “1, 2, 3, 4, 5, 6, 7. Seven”). The stage of the child’s perceptual, concrete addition vs. imagined addition vs. numerical addition will shed light on the child’s performance level. Children’s ability to “see small collections” grows from perceptual (counting concrete objects), to imagined (counting hidden objects and shown objects), to numerical patterns (counting number words) (Clements & Sarama, 2004; Steffe, 1992). According to Clements and Sarama (2004), children who cannot “count on” often follow three steps (e.g., 6+2=?): counting objects from the initial collection of six items, counting two more items, and then counting the items from the two collections together. Since strategies such as counting with fingers vs. “count on” were only partially
recorded, and could have shed light on a better assessment method for the learning performance and the level/stage the children were at, the researcher concluded that for the dissertation study, strategies would be recorded.

The last finding was that the best performance was yielded by the condition of combined Gestural Conceptual Mapping and Direct-Touch variables. Using congruent gestures in touch interfaces seems to be the ideal interface for more immediate counting and adding, as well as improving the accuracy of the answers for both tasks. Four conditions were designed for the dissertation study that would cover all four possibilities within these variables.

**ADDITION TASK RESULTS**

![Bar chart showing comparison of addition task results for different conditions.](chart.png)
Figure 6. Addition Task Results; number of correct answers and time on task (in seconds)

TANAGRAM PUZZLE TASK RESULTS

Figure 7. Tangram Puzzle Task Results; number of correct answers and time on task (in minutes)
CHAPTER 4: THE DISSERTATION STUDY

The present study further explored the effect of Gestural Conceptual Mapping and the Direct-Touch interaction on children’s performance in math. Compared to the pilot study, whose sample consisted of four and five-years-old children with middle-income SES, the dissertation study had a larger sample size and contained older children (six- and seven-year-olds) with low SES profiles. The design focused on two tasks that were based on arithmetic and estimation of numbers. A change in the first arithmetic task (counting and addition) was made to adjust for age-appropriate math abilities. The addition problems included numbers from 1 to 20, and the interface was adjusted to reflect that change. In addition, the second task changed from being a tangram puzzle task to a number-line estimation task. The second task of the number-line estimation was chosen instead of the tangram task used in the pilot study since it is more related to the math concept of counting and addition (magnitude) and could be easily contrasted. This allowed a focus to be placed on the concept of math for the exploration of the use of gestural interfaces to benefit the procedure of a discrete procedure, such as counting, or a continuous procedure, such as estimation of number line.

These two math abilities are believed to emerge from two representational systems; estimation is an intuitive ability that is supported by an evolutionarily ancient approximate number system, and arithmetic relies on symbolic representation that is acquired (Halberda, Mazzocco, & Frigenson, 2008). Number-line estimation is one of the abilities included in number sense theory and is believed to be an intuitive understanding of numbers, magnitudes, and the relationship between them. Dehaene and Cohen (1995)
proposed that the parietal lobe contributes to the representation of numerical quantity on a mental “number line.” Dehaene and colleagues provided evidence that a nonverbal representation of numerical quantity, analogous to a spatial map or “number line,” is present in the horizontal intraparietal region (HIPS) of both hemispheres (Dehaene, Piazza, Pinel, & Cohen; 2003). This representation underlies what a given numerical size means, as well as the proximity relations between numbers. Number sense is the sense of what numbers mean, the ability to perform mental mathematics and to look at the world and make comparisons.

Berteletti, Lucangeli, Piazza, Dehaene, and Zorzi (2010) provide evidence that an understanding of how numbers map onto space develops long before formal education begins. This stands in contrast to counting and addition, which is an arithmetic procedure that requires linear representations of numbers (rather than logarithmic) that believed to be increased with formal education. The concept of numbers in mathematically educated adults implies a linear mapping between numbers and space (Siegler & Opfer, 2003; Zorzi, Priftis, & Umiltà, 2002), so that numbers can be used for measurement. It is controversial as to how both math concepts are achieved, although it is clear that the child’s experience with counting and number words plays a major role (e.g., Le Corre & Carey, 2007). Siegler and collaborators suggested that there is a developmental transition from logarithmic to linear numerical estimation and that children’s representation of numbers changes over time with increasing formal knowledge (Siegler & Booth, 2004; Siegler & Opfer, 2003).

Number-line estimation requires translating a number into a spatial position on a number line, or translating a spatial position on a number line into a number. As noted in Siegler
and Booth’s (2005) review of the estimation literature, numerical estimation is a process of translating between alternative quantitative representations, at least one of which is inexact and at least one of which is numerical. Number-line estimates correlate substantially with other measures of numerical magnitude knowledge, such as magnitude comparison and numerical categorization (Laski & Siegler, 2007). The learning sequence that involves representations of numerical magnitudes is central to understanding the meaning of number symbols (e.g., knowing that “6” denotes six objects), and comparing the magnitudes of numbers (e.g., knowing that six is more than four).

Development of numerical magnitude representations is an important educational problem because the process presents a challenge to many students, and because immature numerical magnitude representations hinder students’ learning in the area of mathematics. In the current study, while performing both tasks, children learned numerical magnitude concepts within a discrete procedure and within a continuous procedure. Understanding how to design these kinds of tasks, which will benefit children’s performance, is critical. Based on action compatibility effect studies, physical manipulation research, and spontaneous gestures studies, the author believes that using gestures congruent with discrete-change problems for arithmetic and with continuous-change problems for estimation would support children mental representations and operations and yield better performance. A continuous action (gesture) would better suit children’s mental operations for the continuous task of number-line estimation, whereas a discrete action would better suit children’s mental operations for the discrete task of counting and adding.
The focus was on two variables of direct manipulation: the Gestural Conceptual Mapping variable and the Direct-Touch variable. Gestural Conceptual Mapping explored mapping of mental operations to physical actions (gestures) of discrete-change problems and of continuous-change problems. Direct-Touch explored the sensorimotor input of direct-touch manipulation (iPad touch interface) vs. less direct touch manipulation (mouse interface). The main research question was whether well-designed gestural interfaces that incorporate a higher level of direct manipulation could facilitate thinking and possibly learning. A more specific research question was whether the Direct-Touch variable and the Gestural Conceptual Mapping variable had a main effect on thinking and performance. The Gestural Conceptual Mapping hypothesis was that children who use congruent gestures with mental operations of discrete-change problems and continuous-change problems would outperform children who use incongruent gestures. The Direct-Touch input hypothesis was that children who use direct-touch interface to manipulate objects on the screen would outperform children who use a mediated mouse interface. A third research question was whether there was an interaction between the properties of direct manipulation. The hypothesis was that children in the condition of congruent gestures and touch interface would have the best performance, and children who are in the condition of incongruent gestures and mouse interface would have the poorest performance. A fourth research question was whether age and technological experience mediates the effect of Direct-Touch and Gestural Conceptual Mapping. The hypothesis was that older children would outperform younger children.

Two usability tests were conducted with users in the design process of the applications. Nineteen six- and seven-year-old children interacted with the different interfaces, and
modifications of both the applications and the research design were made accordingly. This allowed for better control of behavioral mapping.

**Participants**

The researcher recruited 128 subjects who were six and seven years old from 1st and 2nd grade. Twelve children were disqualified due to a mistake in their age (they were eight years old), and nine children were disqualified due to a technical usability problem. In all, 107 subjects were qualified to complete the study, 60 boys and 47 girls. Children were recruited from two after school programs in public schools in a low-SES area of New York City. Data on age and gender were collected.

**Materials**

Two learning tasks with virtual manipulatives examined the effect of high direct manipulation provided by gestural interfaces vs. traditional interfaces. Two educational applications were developed to allow interaction and learning with two math concepts. The learned concepts explored were concepts of discrete-change problems that focus on change over a series of steps, such as counting blocks, vs. concepts of continuous-change problems that focus on change over a single, non-partitioned event, such as number-line estimation. The tasks were counting and addition for the discrete-change problem, and a number estimation on a number line for the continuous-change problem. The gestural interface was a 10” multi-touch iPad device by Apple, and the traditional interface was a Macintosh Macbook Pro laptop by Apple, which requires the use of a mouse. Software developed by the experimenter recorded the child’s answers and the time taken to complete each task. In order to accurately record all children’s strategies, the
The experimenter marked the strategies chosen by the child on a check box strategies list. To allow more qualitative data to be collected, a video camera was placed over the child’s shoulder to capture both the screen and the child’s hand movements (such as counting with the fingers). Children were given a pre-test to assess knowledge of numbers recognition (1-20) and verbal counting of numbers 1-100. In addition, the pre-test included a paper and pencil test that each child filled out. In this pre-test the child completed three tasks. The first task was to solve 10 counting and addition problems (such as: “3+4=?”). The second task was a number-line estimation task, with ten problems to be solved. This number line was a line (not a bar), with “0” at the beginning and “100” at the end. The third task was a “which number is bigger” task, which provided children with 10 sets of two numbers, between 0 and 100, and asked them to specify which is bigger. The near transfer post-test repeated the pre-test paper and pencil test with the same problems in different order. In all of the tasks the children had to circle the answer on the page, or mark the guessed number (in the number-line estimation task). They did not have to write the numbers. Children were not given feedback on the pre- and post-tests. Eight testers were recruited from graduate programs in Teachers College and were paid by the hour. All had previous experience testing children. All testers received a two-hour training session by the researcher. Each tester was given a script to follow (see Appendixes A-D) and was also required to practice the interactions needed to demonstrate for the child within the different interfaces. The testers were told that this was a technology and math study and were not provided with the details of the study goals and research hypotheses.
Procedure

The children were randomly assigned to one of four conditions: the Direct-Touch, and Gestural Conceptual Mapping condition, the Direct-Touch and Gestural Non-Conceptual Mapping condition, the Mouse and Gestural Conceptual Mapping condition, and the Mouse and Gestural Non-Conceptual Mapping condition (see Figure 8). First, all children did a five-minute pre-test. Then, the experimenter conducted two 20-minute sessions intervention with each child (of the four groups), allowing him to solve the two tasks. All children performed two tasks in a counterbalanced order. During all interfaces, the experimenter solved one problem to demonstrate usage and allowed the child to practice solving one problem himself. To measure performance, the computer recorded time on tasks and accuracy of the answers. In addition, the experimenter recorded any strategies that were used by the children. After finishing both tasks, all children were given a ten-minute post-test (paper and pencil) and a near transfer test (to assess transfer of knowledge in addition, estimation of numbers, and magnitude of numbers).

Variables and design

This is a 2x2 between subjects design. There were four conditions (see Figure 8). The direct manipulation was examined in both tasks and included two direct manipulation properties:

- Gestural Conceptual Mapping: Mapping the gesture to the learned concept, which results in better performance. This is a new term defined by this researcher. It explores the compatibility between gestures and digital representations of the learned concepts. Gestures congruent with the learned concepts support thinking and possibly learning.
Children who use well-designed gestural interfaces that map the mental operations to congruent physical actions should perform better than children who use interfaces that do not map the mental operations to congruent physical actions.

- **Direct-Touch Input:** Adding the Direct-Touch to perform these tasks results in better performance. The different levels of sensorimotor input (touch vs. mouse) affect performance. Children who use touch-based interface should outperform children who use mouse-based interface.

Behavioral mapping, which is the third property of direct manipulation, was controlled by usability tests that were conducted in the applications design process. In addition, the experimenter demonstrated how to interact with the application and allowed users to practice.

**Counting and addition task: discrete procedure**

Children were required to solve 10 addition problems by working on a virtual manipulatives interface that showed virtual blocks arranged in side-by-side piles of two 10-block towers. The addition problems ranged from 1 to 20, such as 6+7=? (see Figure 9). The computer narrated the questions so children did not need to recognize the symbols.

**Direct-Touch variable:** The first variable compared the use of the direct-touch interaction vs. mouse interaction, such as tapping with a finger on a multi-touch screen (iPad) to fill in digital blocks in a bar chart, and performing addition vs. filling in the digital blocks by clicking them with a mouse via a traditional interface (see Figure 9). For example, for the question “3+4=?”, the child tapped with a finger (in direct-touch
condition) or clicked with the mouse (in mouse condition) on three blocks on the left column of the bar chart. Each time the child tapped on a block, he highlighted the color of the block. Then the child tapped or clicked (depending on condition) on four blocks in the right column of the bar chart. Each time the child tapped on a block, he highlighted the color of the block. Then the child added these two numbers together and tapped or clicked the green “result” buttons on the bottom.

**Gestural Conceptual Mapping Variable:** The second variable compared the use of Gestural Conceptual Mapping vs. Gestural Non-Conceptual Mapping, both on the multi-touch interface (iPad) and on the traditional interface (mouse). Children either used congruent gestures to the discrete procedure of counting, or not. In the congruent gestures condition, children tapped with their finger on each individual digital block in a bar chart to highlight the block’s color, then performed addition of both columns. This is a congruent gesture that is conceptually mapped to the discrete concept of counting. For example, for the question “3+4=?”, the child tapped on three blocks on the left column of the bar chart, and each time the child tapped on a block he highlighted the color of the block. Then the child tapped on four blocks on the right column of the bar chart, and each time the child tapped on a block he highlighted the color of the block. Then the child added these two numbers together and tapped the green “result” buttons on the bottom (see Figure 9). In the non-congruent gestures condition, children tapped on the numbers under each column of blocks (not on each block), and this automatically highlighted the colors of the blocks, a gesture which is not conceptually mapped to the discrete concept of counting. For example, for the question “3+4=?”, the child tapped on the number “3,” and as a result, on the bottom of the left column in the bar chart, the computer
automatically highlighted three blocks in the left column. Then the child repeated it with the number “4” on the right column. Finally, the child needed to perform the addition of these two numbers and tapped on the green “result” buttons on the bottom (see Figure 9).

**Number-Line estimation task: Continuous procedure**

Children were required to estimate 23 numbers (1-100) on a virtual number line (see Figure 10). The computer narrated the questions so children did not need to recognize the symbols. Prior to the task, the experimenter asked the child to show her if there was the number 0 on the number line, and if there was the number 100, to make sure the child recognized the numbers. The experimenter explained the task by saying, “a number line is a line with numbers across it. The numbers on the line go from the smallest number to the largest number, and the numbers go in order, so each number has its very own spot on the number line.” After each answer, the child received an animated feedback with the numbers appearing on the number line from left to right, up to the correct value (see Figure 11). This is important since the researcher was interested in the learning effect, and proper feedback is expected to reinforce learning.

**Direct-Touch Variable:** The first variable compared the use of the direct-touch interaction vs. mouse interaction in a continuous number-line task. Using a multi-touch interface (iPad), the child slid his finger horizontally on the number line to estimate numbers vs. the traditional (mouse) interface, where the child dragged the mouse horizontally on the number line to estimate numbers.

**Gestural Conceptual Mapping Variable:** The second variable compared the use of Gestural Conceptual Mapping vs. Gestural Non-Conceptual Mapping, both on the multi-
touch interface (iPad) and on traditional interfaces (mouse). Children either used congruent gestures that are mapped conceptually to the continuous magnitude of a number line, or used non-congruent gestures that were not mapped conceptually to the continuous magnitude of a number line (i.e. used a discrete gesture). In the congruent gestures condition, the child slid his finger horizontally (continuous gesture) on the screen to estimate numbers on the number line, vs. the non-congruent condition, where the child tapped (discrete gesture) on the screen to estimate the numbers (see Figure 10). The sliding gesture, in that case, is mapped conceptually to the concept of continuous magnitude of a number line. It is an action congruent with the mental operation of increasing or decreasing something (e.g., a number-line bar) continuously.
<table>
<thead>
<tr>
<th>GESTURAL INTERFACE:</th>
<th>DIRECT-TOUCH, GESTURAL CONCEPTUAL MAPPING</th>
<th>DIRECT-TOUCH, GESTURAL NON-CONCEPTUAL MAPPING</th>
</tr>
</thead>
</table>
| MULTI-TOUCH (iPAD)   | **Addition Task:** Tap with finger on each block, discrete congruent gesture  
|                      | **Number-Line Task:** Slide finger horizontally to reach estimated value, continuous congruent gesture | **Addition Task:** Tap with finger on the number, blocks are highlighted automatically, no discrete gesture, incongruent  
|                      |                                                  | **Number-Line Task:** Tap with finger on estimated value, discrete gesture, incongruent gesture |
| TRADITIONAL INTERFACE: | MOUSE, GESTURAL CONCEPTUAL MAPPING | MOUSE, GESTURAL NON-CONCEPTUAL MAPPING |
| Monitor & Mouse      | **Addition Task:** Click with mouse on each block, discrete congruent gesture  
|                      | **Number-Line Task:** Drag mouse horizontally to reach estimated value, continuous congruent gesture | **Addition Task:** Click on the number, blocks are highlighted automatically, no discrete gesture, incongruent  
|                      |                                                  | **Number-Line Task:** Click with mouse on estimated value, discrete gesture, incongruent gesture |

**Figure 8.** Table of the four conditions. Each condition includes two tasks per child.
Figure 9. Counting and Addition task interface.
Figure 10. Number-Line Estimation Task interface.
Research questions

The main research question is whether well-designed gestural interfaces that incorporate a higher level of direct manipulation could facilitate thinking and possibly learning. A more specific research question is whether the Direct-Touch variable and the Gestural Conceptual Mapping variable have a main effect on thinking and performance. A third research question is whether there is an interaction between the properties of direct manipulation. A fourth research question is whether age and technological experience mediate the effect of Direct-Touch and Gestural Conceptual Mapping.
Hypotheses

The first hypothesis is that children who are in the Gestural Conceptual Mapping condition will outperform children who are in the Gestural Non-Conceptual Mapping condition. Congruent gestures promote performance.

The second hypothesis is that children who are in the Direct-Touch (touch interface) condition will outperform children who are in the Mouse (mouse interface) condition.

The third hypothesis is that children who are in the Direct-Touch and Gestural Conceptual Mapping group (touch interface with congruent gestures) will have the best performance, and children who are in the Mouse and Gestural Non-Conceptual Mapping group (mouse interface with non-congruent gestures) will have the poorest performance.

The fourth hypothesis is that there will be an interaction between the Direct-Touch variable and the Gestural Conceptual Mapping variable.

The fifth hypothesis is that there will be a main effect of age, due to both technological experience and content mastery.

Results

This section will describe the results of the dissertation experiment in depth. The section starts with an overview of the full model. It then follows with an analysis of variance of the full model and states the significant effects found. Each one of the hypotheses will then be presented and the relevant results explained. Finally, an overview of the
descriptive statistics will be presented. The data were analyzed using a 2x2 ANOVA. Regressions were used to analyze the hypothesized interactions and the main effects.

**Overview of the full model: Percent absolute error as the outcome**

\[ Y(\text{Percent Absolute Error}) = X_1(\text{Age}) + X_2(\text{Gestural Conceptual Mapping}) + X_3(\text{Direct-Touch}) \]

The model was found statistically significant across both tasks (see Figure 12). In the Addition Task: \( F(4,102) = 8.034, p < .001, R^2 = .240 \). In the Number-Line Task: \( F(4,102) = 8.616, p < .001, R^2 = .253 \).

**Figure 12.** Means of percent absolute error in both Addition Task and Number-Line Task
Overview of the full model: Time on task as the outcome

\[ Y(\text{Time on Task}) = X_1(\text{Age}) + X_2(\text{Gestural Conceptual Mapping}) + X_3(\text{Direct-Touch}) \]

The model was found statistically significant across both tasks (see Figure 13). In the Addition Task: \( F(4,102) = 51.134, p < .001, R^2 = .667 \). In the Number-Line Task: \( F(4,102) = 9.981, p < .001, R^2 = .253 \).

![Figure 13. Means of time spent on task in both Addition Task and Number-Line Task](image)

**Do Congruent Gestures Promote Performance?**

The main effect of Gestural Conceptual Mapping was significant across both tasks. The percent of absolute error was significantly lower in the Gestural Conceptual Mapping condition. This means that children in the Gestural Conceptual Mapping condition outperformed the children in the Gestural Non-Conceptual Mapping condition. Both in the addition task and the number line task children who used congruent gestures outperformed children who used incongruent gestures.
Addition Task – Dependent Variable: Percentile of Absolute Error

Children who used congruent gestures, such as discrete gestures for the counting and addition task, had significantly lower percent of absolute error than children who used incongruent gestures. This means that children who used interfaces that incorporated Gestural Conceptual Mapping (discrete gestures) for counting and adding outperformed children who used interfaces that did not incorporated Gestural Conceptual Mapping. This was true for both the mouse and the touch interfaces (see Table 1 and Figure 14). In the Addition Task: $F(4,102) = 8.034, p < .001, R^2 = .240, t = -2.902$ ($\text{sig} = .005$).

<table>
<thead>
<tr>
<th>Variable:</th>
<th>Congruent Gestures</th>
<th>Incongruent Gestures</th>
<th>Total:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mouse</strong></td>
<td>.004 (M)</td>
<td>.008 (M)</td>
<td>.006 (M)</td>
</tr>
<tr>
<td></td>
<td>.012 (SD)</td>
<td>.014 (SD)</td>
<td>.013 (SD)</td>
</tr>
<tr>
<td><strong>Touch</strong></td>
<td>.001 (M)</td>
<td>.014 (M)</td>
<td>.007 (M)</td>
</tr>
<tr>
<td></td>
<td>.004 (SD)</td>
<td>.022 (SD)</td>
<td>.016 (SD)</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td>.002 (M)</td>
<td>.012 (M)</td>
<td>.007 (M)</td>
</tr>
<tr>
<td></td>
<td>.008 (SD)</td>
<td>.019 (SD)</td>
<td>.015 (SD)</td>
</tr>
</tbody>
</table>

Table 1. Means of percent absolute error in Addition Task.
Figure 14. Means of percent of absolute error in Addition Task.

**Number-Line Task – Dependent Variable: Percentile of Absolute Error**

Children who used congruent gestures, such as continuous gestures for number-line estimation tasks, had significantly lower percent of absolute error than children who used incongruent gestures. This means that children who used interfaces that incorporated Gestural Conceptual Mapping (continues gestures) for estimating numbers on number-line outperformed children who used interfaces that did not incorporated Gestural Conceptual Mapping (discrete gestures). This was true for both the mouse and the touch interfaces (see Table 2 and Figure 15). In the Number-Line Task: $F(4,102) = 8.616$, $p < .001$, $R^2 = .253$, $t = -2.075$ (sig = .04).
<table>
<thead>
<tr>
<th>Variable</th>
<th>Congruent Gestures</th>
<th>Incongruent Gestures</th>
<th>Total:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mouse</strong></td>
<td>.15 (M)</td>
<td>.16 (M)</td>
<td>.15 (M)</td>
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<td></td>
<td>.07 (SD)</td>
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<td>.06 (SD)</td>
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<tr>
<td><strong>Touch</strong></td>
<td>.13 (M)</td>
<td>.18 (M)</td>
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</tr>
<tr>
<td></td>
<td>.05 (SD)</td>
<td>.08 (SD)</td>
<td>.07 (SD)</td>
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<tr>
<td><strong>Total:</strong></td>
<td>.14 (M)</td>
<td>.17 (M)</td>
<td>.15 (M)</td>
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<tr>
<td></td>
<td>.06 (SD)</td>
<td>.07 (SD)</td>
<td>.07 (SD)</td>
</tr>
</tbody>
</table>

**Table 2.** Means of percent of absolute error in Number-Line Task

![ERROR in NUMBER LINE TASK](image)

**Figure 15.** Means of percent of absolute error in Number-Line Task
**Do Direct-Touch Interfaces promote performance? Time on Task and Strategy Use**

The children who were in the Direct-Touch condition spent significantly less time solving the problems than children who were in the mouse condition. There was a main effect of the Direct-Touch condition across both tasks, when the outcome was time on task.

*Addition Task – Dependent Variable: Time on Task*

Children who used touch interfaces, whether it was with congruent or incongruent gestures, spent significantly less time solving the problems in the Addition Task (see Table 3 and Figure 16): \(F(4,102) = 51.134, p < .001, R^2 = .667, t = -4.660 (\text{sig} = .000)\).

<table>
<thead>
<tr>
<th>Variable:</th>
<th>Congruent Gestures</th>
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</tr>
</thead>
<tbody>
<tr>
<td><strong>Mouse</strong></td>
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<td></td>
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<tr>
<td></td>
<td>40.23 (M)</td>
<td>18.85 (M)</td>
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<td></td>
<td>12.53 (SD)</td>
<td>6.16 (SD)</td>
<td>14.61 (SD)</td>
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<tr>
<td><strong>Touch</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>29.97 (M)</td>
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<td>22.7 (M)</td>
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<td></td>
<td>9.43 (SD)</td>
<td>4.92 (SD)</td>
<td>10.69 (SD)</td>
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<tr>
<td><strong>Total:</strong></td>
<td>34.63 (M)</td>
<td>16.73 (M)</td>
<td>25.93 (M)</td>
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<tr>
<td></td>
<td>12.01 (SD)</td>
<td>5.82 (SD)</td>
<td>13.06 (SD)</td>
</tr>
</tbody>
</table>

*Table 3.* Means of time spent on task in Addition Task
Children who used touch interfaces, whether it was with congruent or incongruent gestures, spent significantly less time solving the problems in the Number-Line Task (see Table 4 and Figures 17-19): $F(4,102) = 9.981, p < .001, R \text{ square} = .253, t = -4.967 (\text{sig} = .000)$. 

**Figure 16.** Means of time on task in Addition Task
<table>
<thead>
<tr>
<th>Variable:</th>
<th>Congruent Gestures</th>
<th>Incongruent Gestures</th>
<th>Total:</th>
</tr>
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<tbody>
<tr>
<td>Mouse</td>
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<td>10.54 (M)</td>
<td>11.88 (M)</td>
</tr>
<tr>
<td></td>
<td>5.52 (SD)</td>
<td>4.43 (SD)</td>
<td>5.14 (SD)</td>
</tr>
<tr>
<td>Touch</td>
<td>9.13 (M)</td>
<td>7.03 (M)</td>
<td>8.12 (M)</td>
</tr>
<tr>
<td></td>
<td>3.05 (SD)</td>
<td>2.42 (SD)</td>
<td>2.93 (SD)</td>
</tr>
<tr>
<td>Total:</td>
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<td>8.65 (M)</td>
<td>9.84 (M)</td>
</tr>
<tr>
<td></td>
<td>4.76 (SD)</td>
<td>3.88 (SD)</td>
<td>4.49 (SD)</td>
</tr>
</tbody>
</table>

Table 4. Means of time spent on task in Number-Line Task

Figure 17. Means of time on task in Number-Line Task
Children who were in the Direct-Touch condition used an advanced strategy significantly more times to solve the addition task than children who were in the mouse condition. This means that the touch interface provided a setting that encouraged more advanced problem solving. The advanced problem solving in particular was measured through the use of the “count on” strategy. The “count on” strategy is when children add two sets of numbers in a more immediate way; they count the first set of blocks and then continue by
adding the second number immediately, in a sequenced progression. For example, for the equation “5+7” a child will start by counting five, “1, 2, 3, 4, 5,” and will continue by adding seven, “6, 7, 8, 9, 10, 11, 12.” This is compared with the more time-consuming strategy of counting the seven blocks separately from the five blocks, and then adding the two numbers together using addition for the third time. For the analysis of these data we combined all “count on” strategies, meaning that the “count on” for 10+10 problem, the “count on from big number,” and the “count on from small number” were combined. Children in the Direct-Touch condition outperformed the children in the Mouse condition for strategy use in the Addition Task (see Figures 20 and 21): $F(3,103) = 2.951, p < .001.$

*Figure 20.* Touch interface vs. mouse interface interactions in addition task
As discussed, the children in the Direct-Touch condition, both in the Touch, congruent gestures condition and Touch, incongruent gestures condition, used the advanced “count on” strategy significantly more times (between 3-5 times) than the children in the Mouse condition (less than 3 times) (see Figures 21-25). Moreover, children who used the advanced “count on” strategies also had a lower percentile of error than children who did not use these strategies (see Figure 26): $F(5, 101) = 7.481, p < .05$ ($\text{sig} = .042$)
Figure 22. Means of total number of times of combined “count on” strategies use in Addition Task.

Figure 23. Means of number of times of “count on from big number” strategy use in Addition Task.
**Figure 24.** Means of number of times of "count on from small number" strategy use in Addition Task.

**Figure 25.** Means of number of times of "count on" for "10+10 question" strategy use in Addition Task.
Figure 26. Means of number of times of "count on" strategies use in Addition Task and percent of absolute error.

Count with fingers strategy

There was no significant difference between Children in the Direct-Touch condition compared to the children in the Mouse condition in counting with fingers strategy (see Figure 27).
Count with fingers on screen strategy

Children in the Direct-Touch condition counted more with their fingers on the screen than children on the Mouse condition. In the touch and congruent gestures condition they were required to count on the screen, however, in the touch and incongruent gestures condition, children were not required to count on the screen and still did it more often than children in the mouse condition (see Figure 28). This may be because they did not need to hold a mouse in their hand, and the touch screen encourages touching it directly and counting the virtual blocks with fingers.

**Figure 27.** Means of number of times of "count with fingers" strategy use in Addition Task.
**Figure 28.** Means of number of times of “count with fingers on screen” strategy use in Addition Task.

**Count with cursor on screen strategy**

Children in the Mouse condition counted more with their cursor on the screen because children in the Direct-Touch condition did not have a mouse. In the mouse and congruent gestures condition, children were required to count on the screen with the cursor. However, in the mouse and incongruent gestures condition children were not required to count on the screen and still did it often (see Figure 29).
**Count with eyes strategy**

There was no significant difference in the degree to which number of times children in the four conditions counted with their eyes (see Figure 30).
Figure 30. Means of number of times of “count with eyes” strategy use in Addition Task.

Automatic (no counting) strategy

Children in the Gestural Conceptual Mapping and Direct-Touch condition (congruent gestures and touch interface) hardly used automatic strategy (no counting) at all. Children in the Gestural Non-Conceptual Mapping conditions (incongruent gestures) used automatic strategy more than children in the Gestural Conceptual Mapping conditions (see Figure 31). Furthermore, children who used the automatic strategy (no counting) also had the highest percent of error than children who did count, which means their addition performance was poorer than that of children who counted (see Figure 32): $F(5, 101) = 21.376, p < .001, (\text{sig} = .000)$
**Figure 31.** Means of number of times of “automatic (no counting)” strategy use in Addition Task.

**Figure 32.** Means of number of times of “automatic (no counting)” strategy use in Addition Task and percent of absolute error.
Other strategies

Children in the Gestural Conceptual Mapping and Mouse condition (congruent gestures and mouse interface) used other strategies more than children in other conditions (see Figure 33). Examples of other types of strategies are: 1) Counting the blocks from side to side, 2) Adding the sum on the green buttons (these are the buttons 1-20 that the subject need to press for the answer), 3) Counting the blocks from top to bottom rather than bottom to top, 4) Using both fingers and toes to count and add (one child), and 5) Asking to count on the tester’s fingers in addition to the child’s own fingers (one child).

Figure 33. Means of number of times of "other" strategy use in Addition Task.
Overview of all strategies used

Children used many different strategies to solve the problems given to them. In order to capture all of these strategies the testers recorded all strategies the children used while answering each question. For example, if a child used the “count with fingers on screen” strategy and also counted with their own fingers, the testers recorded both.

Some interfaces prompted using one strategy vs. another. For example, children who where in the mouse interface conditions used more of the “counting with cursor on screen” strategy, than “counting with fingers on screen” strategy. In summary, children who were at the direct-touch interfaces conditions used the advanced “count on strategy” more than children who were in the mouse interfaces conditions. Also, children who used the automatic strategy, and did not count in any form, had the poorest performance. See figure 34 for overview of all strategies used across conditions.
Figure 34. Overview of all strategies used in addition task.
**Best Performance with Combined Congruent Gestures and Touch Interface**

Children in the Direct-Touch, Gestural Conceptual Mapping condition had the best performance across both tasks. They had the lowest percent of absolute error.

However, children who were in the Mouse, Gestural Non-Conceptual Mapping condition had only the second poorest performance across both tasks. The children who were in the Direct-Touch, Gestural Non-Conceptual Mapping condition had the poorest performance.

This means that actions affected performance and that congruent gestures were important for cognition, especially when combined with the Direct-Touch, but not only then. Congruent gestures were also effective in the Mouse condition at facilitating better performance.

In relation to strategy use, children who were in the Direct-Touch, Gestural Conceptual Mapping condition used the most advanced strategies of all the other children. Children who were in the Mouse, Gestural Non-Conceptual Mapping condition used the least advanced strategies.

**Is there Interaction Between Gestural Conceptual Mapping and Direct-Touch?**

There was no significant interaction between the Direct-Touch variable and Gestural Conceptual Mapping variable. However, in the time spent on addition task there was a near-significant interaction between the variables. Time as an outcome: \( F(4,102) = 51.134, \ p < .001, \ R \ square = .667, \ Interaction = .054 \)
Older Children Outperform Younger Children

There was a main effect of age across both tasks with both dependent variables. Older children outperformed younger children and it took them less time to complete the tasks. This could be attributed not only to usability and technological experience but also probably mainly to content mastery and cognitive development level. With dependent variable percent absolute error: In the Addition Task: $F(4,102) = 8.034$, $p < .001$, $R^2 = .240$, $t = -4.036$ ($sig = .000$); in the Number-Line Task: $F(4,102) = 8.616$, $p < .001$, $R^2 = .253$, $t = -4.994$ ($sig = .000$). With dependent variable time on task: In the Addition Task: $F(4,102) = 51.134$, $p < .001$, $R^2 = .667$, $t = -4.036$ ($sig = .000$); in the Number-Line Task: $F(4,102) = 9.981$, $p < .001$, $R^2 = .253$, $t = -2.247$ ($sig = .027$).

Pre- and Post-tests

Children were given a pre-test before the computer intervention and post-test after the intervention. They were required to solve three types of problems with paper and pencil: additions problems, number-line estimation problems, and which number is a bigger problem. A $t$-test was performed to find a difference in total score of pre-test compared to total score of post-test. No significant difference was found between the pre- and post-test for the score difference within the three tasks, $t = .350$ ($sig = .727$) (See Figures 35-37).
Figure 35. Score difference between post- to pre-tests in Addition task.

Figure 36. Score difference between post- to pre-tests in Number-Line task.
After completing the intervention, children in all four conditions were given a motivation question. They had to choose an icon that described their motivation to play the intervention tasks. They chose from a smiley face, natural face, or a sad face. All children but five chose the smiley face. From the five children, four children chose the neutral face and only one child chose the sad face. One child did not answer it. This means that most children were motivated to play the games on the iPad (touch interface) or the computer (mouse interface). The five children who were less motivated had worked on the computer within both conditions (congruent and incongruent gestures).

**Motivation Post Test**
Descriptive Statistics: Frequencies

There were 60 boys and 47 girls. There were 5 five-year-old subjects (who were nearly six), 55 six-year-old subjects, and 47 seven-year-old subjects. Of the 107 subjects, 45 were from PS 115 school and 62 were from PS 173 school (see Figures 38-43).

![Figure 38. Frequencies of subjects across gender](image)
Figure 39. Frequencies of subjects across age

Figure 40. Frequencies of subjects across school
**Figure 41.** Distribution of subjects across conditions within gender.
Figure 42. Distribution of subjects across conditions within age.

Figure 43. Distribution of subjects across conditions within schools.
CHAPTER 5: DISCUSSION

The dissertation study focused on exploring whether designed gestures for gestural interfaces could augment thinking, and if so, what would be the best design for that. The comparison was done between gestural touch based interfaces and traditional mouse based interfaces. The author hypothesized that designing gestures that are congruent with the learned concepts and congruent to the graphic (external) representation, would support thinking and yield better performance. This was defined as Gestural Conceptual Mapping. In addition to the congruency variable, the author also hypothesized that the direct-touch based interfaces would support performance better than the mouse based interfaces, especially in relation to efficiency. This means that children who use direct-touch interfaces would spend less time on task and use more advanced strategies than children who use mouse interfaces. The touch interfaces provide spatial contiguity of gesture and diagram (graphic representation), which promotes efficiency on task. The results confirmed these predictions.

*Actions Affect Cognition when They Are Congruent with the Thinking*

Actions on objects in the world have perceptual consequences, where as, mental actions on symbolic objects have symbolic consequences. These “mappings”, from real world actions on objects to mental actions on objects, need to be congruent. When children are learning, it helps to externalize the mental actions on symbolic objects, to physical actions on physical objects, and later with practice the mechanism gets internalized.
Confirming the hypotheses, a statistically significant model was found that revealed a significant main effect for Gestural Conceptual Mapping when the outcome is percent of absolute error. These findings contribute to the action compatibility effect research by providing further evidence that mapping mental operations to congruent physical actions promotes thinking. Specifically, in the present study, mapping the mental operations of discrete magnitude to the discrete gestures, and mapping the mental operation of continuous magnitude to continuous gestures, resulted in better performance. The math problems of arithmetic and estimation explored in this study are mathematical procedures (rather than a gear operation concept that is more concrete). The current study shows that even these abstract concepts could be supported by congruent gestures for facilitating thinking, providing robust evidence in support of the embodied cognition theory.

The findings of the present study suggest the importance of designing congruent gestures with the learned concept. The Gestural Conceptual Mapping supports cognition and possibly learning. Therefore, it should be considered for application with other types of math concepts that include spatial representations. An example could be geometrical concepts that involve mental rotations and mental transformations. The tangram task that was used in the pilot study should be further explored in the context of congruent gestural usage. It involves mental procedures that could be mapped to physical actions, such as rotating the shapes with fingers rather than tapping to rotate (which is an incongruent gesture). Another example that involves spatial skills could be a folding and unfolding paper task, which involves the transformation of shapes (in a virtual environment). An additional mathematical concept could be number comparison, in which young children compare quantities with congruent gestures to make a one-to-one correspondence of
objects (i.e. comparing three apples to five pears). Up and down, short and long, or big and small hands/fingers congruent gestures could also be used in context for various learning tasks.

Other domains such as literacy, physics, mechanics, and music could benefit from Gestural Conceptual Mapping as well. The use of congruent gestures for tracing letters, or congruent actions to support beat and rhythm, should support performance in these areas. Congruent embodied metaphors (gestures), that illustrate different forces in physics or the mechanism of machines, could also benefit from the comprehension of these learned concepts. In general, the findings provide further insight into the effect of gestures on cognition and possibly learning. In order to further test for meaningful learning, researchers should incorporate pre- and post-tests that are better designed with near and far transfer tasks. More detailed suggestions regarding this are given at the end of the discussion.

The use of congruent gestures was beneficial not only when used with touch interface, but also when used with the mouse interface. This means that when designing for mouse interaction, one should consider using congruent actions to the learned concept as well. However, the best performance of accuracy was the combination of the touch interface and the congruent gestures. The combination of these two properties of direct manipulation yielded the best results, implying that when designing for educational technology one should consider mapping physical actions (gestures) to mental operations, and also allowing a higher level of sensorimotor input by using touch interfaces.
Can Congruent Gestures Benefit Thinking with Free-Form Gestural Interfaces?

Physical manipulation of objects that combines compatible movement and direct touch could benefit mental model construction of learned concepts. However, because Gestural Conceptual Mapping (congruent gestures) has a more critical effect on learning than Direct-Touch, for the purpose of supporting performance, it is fair to assume that free-form gestural interfaces that do not involve touch, (such as the Kinect interface) could also support cognition when designed with congruent gestures. The direct-touch interface variable cannot be generalized in the same way as the congruent gestures variable. It appears that, for certain tasks, direct touch would be important to consider, and for other tasks, free-form gestures should be applied (with free-form gestural devices). The properties defining the level of direct manipulation that benefit the user depend on the type of task. For example, a task such as driving a car (in a virtual environment) should be easier when holding a steering wheel device, rather than steering by putting your hands in the air to navigate the car. The Direct-Touch input would be critical in such a task. On the other hand, using free-form gestures, such as rotating one’s head and body in different directions to navigate one’s avatar, would be more direct and intuitive than using a control device.

For the counting and addition task, using one’s own fingers to count and add on the screen (on the iPad) was intuitive and embodied the learning experience for the children. Ginsburg (1989) claims that children’s strategy to count on their own fingers is almost
inseparable from the process of learning how to count. By doing so, they are embodying their own counting experience. By using a touch interface for that task (with congruent gestures for counting), children do not need to count on their fingers; the interface incorporates their embodied experience of counting on the screen with their own fingers. The present study brings further evidence that supports the importance of physical manipulation for cognition. The children who did not embody their addition process by counting either with their fingers, with their fingers on the screen, or with the cursor, but added the numbers automatically, had the poorest performance.

**Touch Interfaces Are More Efficient Than Mouse Based Interfaces**

Confirming the hypothesis, a statistically significant model was found that revealed a significant main effect for the Direct-Touch for time on task. Children spent much less time on task when using the touch interfaces. This means they could potentially have more time to practice problems if they use touch-based interfaces compared to mouse-based interfaces. This could have critical implications for using touch-based interfaces in classrooms and at home, potentially leading to better learning. This finding is mainly related to behavioral mapping, that is, the control of the user on the interface from a usability perspective. Touch-based interfaces allow easier interaction than mouse-based interfaces, especially for young children whose fine motor skills are below those of older children and adults. Research regarding children’s pointing skills showed differences in path-to-target and accuracy; younger children were less direct and needed targets four times larger in diameter than young adults to achieve accuracy (Baauw, Bekker, & Barendregt, 2005; Hourcade, Bederson, & Druin, 2004; Hourcade, Bederson, Druin, & Guimbretière, 2004). Another skill that could be attributed to the time spent on task with
mouse interfaces is visual-motor coordination. Gallahue and Ozmun (2002) found that children using a mouse interface could track objects moving on a horizontal plane starting at five years old, and could track objects moving on an arc starting at eight years old. The use of direct touch better supports the visual-motor coordination, and makes it easier (and therefore faster and more accurate) to track objects on the screen.

The findings also suggest that Direct-Touch allows for better use of strategies. Furthermore, there was a correlation between children’s use of the “count on” strategies and their performance, strengthening the fact that children who used the “count on” strategy were more advanced in their math level. This means that touch-based interfaces could benefit thinking and possibly learning on certain tasks. Children who used the iPad preformed the advanced “count on” strategies significantly more times than other strategies. This could be attributed to working memory. Since the interaction with the touch interface allowed better flow than the mouse interface, children had an easier time remembering the total number (quantity) in the left column while directly continuing to add by “counting on” the numbers in the right column. This is opposite to the mouse interface findings, where it took longer for the child to move from the left column of blocks to the right column of blocks. Based on Baddeley’s (1992) definition of working memory as a system that provides temporary storage and manipulation of information necessary for cognitive tasks, it seems like children in the touch condition had an easier time applying the visuospatial sketchpad needed to prompt the use of the “count on” strategy. The flow and fast pace of interactions that are enabled by the touch interface, benefit the central executive of the working memory, which controls for attention and coordination of resources.
**Do All Digital Devices Interactions Fit into the Embodiment Direct Manipulation Definition?**

One can argue that not all digital devices and interfaces can fit into the scale of direct manipulation as defined by the embodiment theory. This means that for some tasks, interfaces that incorporate external control devices, to manipulate objects on the screen rather than using one’s own body, would be more natural and direct. For example, using a stylus vs. using one’s own finger for a writing task could possibly be more natural and yield better performance. This is especially evident for adults, who are used to writing with a pen and take into consideration that the current interfaces are not sensitive enough to translate the movement of the finger into the fine motor skills movements needed to write text. However, for young children who are learning to write, using one’s finger to trace letters could be more beneficial than using a stylus, because their fine motor skills are not as developed as adults. Based on the embodiment theory, by tracing letters directly with ones own body, one could better process the information and internalized the concept. In summary, the property of direct manipulation of congruent actions (gestures) to the learned concept (Gestural Conceptual Mapping) could be generalized and applied to all digital devices (whether the device includes an external control device or not). Lastly however, the haptic feedback variable and the direct-touch variable are different from task to task across various digital device interfaces, and, cannot be generalized in the same way as the congruency principal.
**Congruency of Visual Feedback to Gestures**

There were possibly two limitations in regards to the design of the addition task. One can argue that the visual feedback was not identical in both the congruent and incongruent conditions in the addition task. In the congruent gestures condition, children who manipulated each discrete block highlighted each individual block on the screen, whereas, in the incongruent gestures condition, children clicked/tapped once on the total symbol number of blocks and the computer highlighted all the blocks at once. Therefore, it is hard to conclude whether the effects were due to making the movements (gestures), or, making the movements (gestures) on virtual objects and seeing the consequences of the actions. A better design could possibly have been presenting the exact same discrete visual feedback so that the blocks in the incongruent gestures would have been highlighted one after the other in a discrete way (animated). However, the decision to make the visual feedback as it was, based on the claim that the action (gesture) should be mapped congruently to the changes in the graphic display. In the addition task, for the discrete congruent gestures condition, each tap gesture (on each individual block) colored one block. For the continuous incongruent gestures condition, one tap gesture (on the total symbol number) colored all the blocks at once.

In the number line task, the visually animated feedback was identical in both the congruent and incongruent gestures conditions. Based on this result, the researcher can conclude that the effects were due to making the movements (gestures) and not due to making the movements (gestures) on virtual objects and seeing the consequences of the actions.
Another design element in the addition task that could have effected the results is; that the children in the incongruent gestures condition had an advantage in that the computer highlighted for them the correct number of blocks, whereas the children in the incongruent gestures condition had to highlight the correct number of blocks themselves, and this could have allowed for mistakes while highlighting. While the children in the incongruent gestures condition had this advantage, they still performed worse than the children in the congruent gestures condition; this only strengthens the hypothesis. A better identical design for both conditions, could have been limiting the number of blocks that could be highlighted, to the number of blocks in the problem. For example, for the problem 5+7, the available number of blocks could have been 5 (instead of 10) on the left and 7 (instead of 10) on the right, so children cannot get the wrong number of blocks when manipulating each individual block.

**Better Design for Pre- and Post-tests**

There were a few limitations to the design in regard to the pre- and post-test results. The first limitation is that the pre- and post-tests included only abstract symbols of numbers and did not include any objects/manipulatives, as in the intervention. Research (e.g., Kaminski, Sloutsky, & Heckler 2009) shows that, children find it harder to transfer knowledge when moving from physical manipulatives to abstract symbols. It is possible that a fading process could have supported the transfer between the real representations of numbers/quantity (virtual manipulatives), to the abstract representations of number symbols. Sarama and Clements (2009) argue that virtual manipulatives are ideally suited for this task because they can be programmed to make instantaneous links between manipulatives and corresponding symbols in real time. In the virtual environment,
learners can manipulate one representational format (manipulatives or symbols) and immediately observe the effects on the other representational format. Brown, McNeil, and Glenberg, (2009), claim that it is critical to note a related mechanism for connecting the concrete to the abstract. They suggest that gesture could relate concrete action to abstract symbols and operations, in a way that can guide students’ attention to important relations.

The second limitation is that the pre- and post-tests and interventions were all done in the same session. Children spent 50 minutes in total on the experiment. The sessions took place in an after school program between the hours of 3:00 and 6:00pm. The children, at this young age, considering the time of day and their schedule, were likely to have been tired, and not very focused when they got to the post-test stage of the study. A better design could have separated the pre- and post-test sessions by conducting each on a different day.

Finally, a third limitation was that children had only one session of intervention. It has been widely shown that in order for learning and transfer to happen, one needs to have repeated sessions of intervention. In order to achieve a learning effect, a long-term study with multiple interventions would be a better design.

Conclusions

**Action supports cognition if the action is congruent with the thinking**

Gestural Conceptual Mapping (congruent gestures) promotes performance. Children who used discrete gestures to solve arithmetic problems, and continuous gestures to solve
number estimation, performed better. Thus, action supports thinking if the action is congruent with the thinking.

**Touch interfaces are more efficient than mouse interfaces and promote using advanced strategies**

Children who used a touch interface applied an advanced “count on” strategy for arithmetic, more frequently than, children using a mouse. Children who used a touch interface spent less time on tasks. Touch interfaces show promise for teaching and learning.

**Significance**

More empirical studies by cognitive psychologists, educators, and human-computer interaction researchers are needed to answer the question of whether the design of innovative gestural interfaces could have effects on cognition and learning, and, more specifically, on young children’s learning and mental model construction. So far, there is not enough research on the use of gestural interfaces by children for the purpose of learning. These gestural interfaces will soon become an integral component amongst educational tools for children, and, quite possibly, enter the realm of early childhood education. Interfaces could provide more concrete experiences, because they require us to use our body in a more direct way, thereby possibly creating more meaningful learning experiences for young children. It is critical to do research in this field and develop some guidelines for designers and educators on how to develop effective gestural interfaces for the purposes of improving cognition and learning.
REFERENCES


APPENDIX A: Script for testers of Touch-Congruent Gestures condition

Date:__________________

Subject’s #:_____________Group: TOUCH, CONGRUENT

Subject’s First & Last Name:__________________________________________

Date of Birth:-__________ Tester name:____________________

Technology & Math Study, August 2010
by Ayelet Segal, Teachers College

PROCEDURE

The children will be randomly assigned to one of four conditions groups. First, all children will do a ten-fifteen minutes pre-test (paper and pencil). Than, the experimenters will conduct two 20 minutes sessions interventions with each child allowing him to solve the two tasks on the computer. During all interfaces, the experimenter will solve one problem to demonstrate usage and allow the child to practice solving one problem himself. To measure performance, the computer will record time on tasks and percentage of accuracy of the answers. In addition, the experimenter will record any strategies that were used by the children. After finishing both tasks, all children will be given a ten minutes post-test (paper and pencil). In total, each session with a child will last about 50 minutes.

PRE-TEST

10-15 minutes for pre-test (paper and pencil)

Children will be given a pre-test that includes five tasks. The first two tasks purpose is to assess knowledge of numbers recognition (1-20) and verbal counting of numbers 1-100. In addition, in this pre-test the child will complete three more tasks: The first task will be to solve ten counting and addition problems (such as: “3+4=?”). The second task will be number line estimation task, with ten problems to be solved. This number line will be a line with “0” at the beginning and “100” at the
end, with no other number marks. The third task will be a “which number is bigger”
task, which will provide children with 10 sets of two numbers, between 0 and 100,
and ask them to specify which one is bigger.

PRE-TEST SCRIPT & ANSWERING PAGE

The script: ” Hi, my name is ....what’s your name? (Experimenter will write down the
name of the child on this answers page).

Today we will play some number games together, some of the games will be on
paper and some on the computer, are you ready? Great, Let’s start.”

Pre-test: Task 1: Assessing recognition of numbers 1-20

Point with your finger to a number from the list (according to the list order) and ask
the child which number is it, make sure you are covering the other numbers with a
paper. Write down the number that the child verbalize on this answers page.

The script: “In this game, I will point to a number and I would like you to tell me
which number it is?”

__ 20
__ 11
__ 2
__ 16
__ 9
__ 15
__ 8
__ 12
__ 19
__ 1
__ 4
__ 18
__ 3
Pre-test: Task 2: Assessing recognition of numbers 1-100

Ask the child to count verbally from 1-100, (do not show him the numbers on the page) mark on the answers page each number that the child does not manage to count verbally.

The script: "This is another game, can you count from 1-100? Ready? go!"

1, 2, 3, 4, 5, 6, 7, 8, 9, 10,
11, 12, 13, 14, 15, 16, 17, 18, 19, 20,
21, 22, 23, 24, 25, 26, 27, 28, 29, 30,
31, 32, 33, 34, 35, 36, 37, 38, 39, 40,
41, 42, 43, 44, 45, 46, 47, 48, 49, 50,
51, 52, 53, 54, 55, 56, 57, 58, 59, 60,
61, 62, 63, 64, 65, 66, 67, 68, 69, 70,
71, 72, 73, 74, 75, 76, 77, 78, 79, 80,
81, 82, 83, 84, 85, 86, 87, 88, 89, 90,
91, 92, 93, 94, 95, 96, 97, 98, 99, 100.

Pre-test: Task 3: Assessing addition 1-20
Read the addition question to the child and ask her to mark the answer to each question below. Demonstrate one question. (make sure you cover with a paper the question below the one you are asking)

**The script:** “Let me ask you a few more questions before we go on to the computer game. These are addition questions. For example, how much do 3 and 5 make? 3 and 5 makes together 8, so I am circling the answer 8 here below. Now you can try the next question.”

\[3 + 5 = ?\]
1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20

\[10 + 2 = ?\]
1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20

\[5 + 9 = ?\]
1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20

\[7 + 2 = ?\]
1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20

\[3 + 8 = ?\]
1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20
6+6=?
1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20

5+6=?
1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20

9+7=?
1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20

3+10=?
1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20

7+3=?
1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20

Pre-test: Task 4: Assessing number line estimation 1-100

The script: “the next game is a guessing game. This is a number line from 0 to 100. A number line is a line with numbers across it. The numbers on the line go from the
smallest number to the largest number, and the numbers go in order, so each number has its very own spot on the number line. Can you point to number 0 on the number line? Now to number 100.

*The experimenter will write down if the child pointed correctly to the numbers 0 and 100:

_____ 0 _____100

Good, let me show you one example”

"Where is number 65? I think it is here, so I make a line with the pencil, you can do the next one”

Read the question number to the child and ask him to make a vertical line with a pencil of the place of the number on the number line.

65
___ 82
___ 30
___ 4
___ 17
___ 76
___ 45
___ 90
___ 15
___ 24
___ 8

**Pre-test : Task 5: Assessing magnitude of numbers 1-100**

Explain the child to circle with a pencil the bigger number from both numbers. Demonstrate one question.
The script: “This is the last game before the computer game. You need to find out which number is bigger. For example, which number is bigger 25 or 12, I’m making a circle around the number that is bigger, I think that 25 is bigger than 12, now you can do the next one”.

25 or 12
35 or 67
89 or 12
6 or 23
12 or 15
93 or 83
10 or 41
55 or 58
72 or 11
41 or 63
97 or 77

*Please give the child his first sticker and promise that there are two more stickers that he will have when he will finish all the games.

INTERVENTION (computer games):

1. NUMBER LINE TASK (max 20 min)

Children will be required to estimate 23 numbers (1-100) on a virtual number line. The computer will narrate the questions so children will not need to recognize the symbols. Prior to the task, the experimenter will explain what is a number line and ask the child to show her if there is zero on the number-line and if there is the number one hundred, to make sure the child recognizes the numbers.

*The experimenter will enter the subject’s number and the child’s first and last name to the log on box.
**The Script:** “This is a number line. A number line is a line with numbers across it. The numbers on the line go from the smallest number to the largest number and the numbers go in order. Each number has its very own spot on the number line.

The experimenter will demonstrate one question and will allow the child to try out another question: "where is the number 95? I believe it is here (The experimenter will tap on the red line and drag his finger until he reaches number 95 on the number line and then tap on the done button), you can go back and forth but once you press the “done” button you can’t change your answer. Now you can try, where is the number 90? Good, now press the done button”

*The experimenter will mark the strategies that the child use (on the strategies page) for each question.*

**Strategies Table for Number-Line Task:**

| Strategies/Problem | 25 | 52 | 87 | 5 | 40 | 64 | 45 | 71 | 33 | 14 | 85 | 68 | 55 | 15 | 30 | 75 | 92 | 7 | 27 | 10 | 51 | 66 | 70 |
|--------------------|----|----|----|---|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|----|
| Use finger         |    |    |    |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Use finger on screen |  |    |    |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Going back and forth w/ cursor/finger | |    |    |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
| Count 10,20, etc with finger on screen | |    |    |   |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |    |
After the child will finish the last question, the experimenter will ask the child:

1. "How did you decide where each number is?"

The experimenter will write down the child’s answers.

(see an example of more following questions, depending on the child’s answer)

E: What did you use to help you decide where to put the numbers?
C: My brain.

E: What was your brain telling you?
C: Put it like in the middle or the end.

E: How did you know if it went in the middle or if it went on the end?
C: Because the low numbers go at the other end and the high numbers go at the other end.

E: What goes in the middle?
C: The mediumest numbers.

2. COUNTING AND ADDITION TASK (max 20 min)

Children will be required to solve ten additions problems by working on a virtual manipulative interface, that shows virtual blocks arranged in side by side piles of two 10 block towers. The addition problems will range from 1-20, such as, 6+7=? 2+9=?
The computer will narrate the questions so children will not need to recognize the symbols. The experimenter will demonstrate one question on the computer (3+4=? ) and will allow training of the second question (2+1=?).

*The experimenter will enter the child’s first and last name to the log on box

**The script: "This is a blocks game, you need to figure out how many blocks are in the left and right piles. For example, how much does 3 and 4 makes together? (The experimenter will tap with his finger on each of the three blocks on the left pile and each of the 4 blocks on the right pile to highlight the color, then he will tap on the answer 7 below), 3 and 4 makes 7 together, so I press the number 7 on the green button, now it’s your turn to try the next one. Remember that you only have one trial for each question and that you have to click on the numbers below each columns before you answer"

*The experimenter will mark the strategies that the child uses (on the strategies page) for each question.

<table>
<thead>
<tr>
<th>Strategies/Problem</th>
<th>9+3</th>
<th>2+8</th>
<th>5+2</th>
<th>7+5</th>
<th>1+10</th>
<th>6+3</th>
<th>9+5</th>
<th>4+6</th>
<th>8+7</th>
<th>10+10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Count on</td>
<td></td>
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<td></td>
<td></td>
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<td>Count with fingers</td>
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<td>Count with fingers on screen</td>
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<td>Count on from big numbers</td>
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<th>Count on from small numbers</th>
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<td>Counting with cursor on screen</td>
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<td>Counting with eyes</td>
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<td>Automatic (no counting)</td>
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<td>Other</td>
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*After the child will finish the **last question**, the experimenter will ask the child:

“1. How did you do that?

2. Could you have done it in a different way?”

*The experimenter will write down the child’s answers.

*Please ask the child “2. Do you like these computer games (the blocks and/or the number line games)? Please mark here how much you like it” Show the child the faces symbols, so he can mark the one that describes his likelihood for the computer games. Add below any comments that the kids describe.
*Please give the child his second sticker.

**POST-TEST**

**10 minutes for post-test (paper and pencil)**

Children will be given a post-test that includes three tasks. In this post-test the child will complete three more tasks: The first task will be to solve ten counting and addition problems (such as: “3+4=?”). The second task will be number line estimation task, with ten problems to be solved. This number line will be a line with “0” at the beginning and “100” at the end, with no other number marks. The third task will be a “which number is bigger” task, which will provide children with 10 sets of two numbers, between 0 and 100, and ask them to specify which one is bigger.

**POST-TEST SCRIPT & ANSWERING PAGE**

Please make sure the child got his second sticker after finishing the computer games. Also, please offer the child to drink some water before continuing and using the bathroom.

**The script:**

You did great on the computer, we are almost done, now we have a few last games together (then you can have your last special sticker), are you ready? Great, Let’s start.”

**Post-test : Task 1: Assessing addition 1-20**
Read the addition question to the child and ask her to mark the answer to each question below. Demonstrate one question. (make sure you cover with a paper the question below the one you are asking)

The script: “These are addition questions. For example, how much do 3 and 5 make? It makes together 8, so I am circling the answer 8 here below. Now you can try the next question”

3 + 5 = ?
1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20

10 + 2 = ?
1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20

7 + 2 = ?
1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20

5 + 9 = ?
1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20

3 + 8 = ?
1 2 3 4 5 6 7 8 9 10
11 12 13 14 15 16 17 18 19 20
The script: “the next game is a guessing game. This is a number line from 0 to 100. A number line is a line with numbers across it. The numbers on the line go from the smallest number to the largest number, and the numbers go in order, so each number has its very own spot on the number line. Can you point to number 0 on the number line, and now to number 100. Good, let me show you one example”

“where is number 65? I think it is here, so I make a line with the pencil, you can do the next one”

Read the question number to the child and ask him to make a vertical line with a pencil of the place of the number on the number line.

65
___ 76
___ 45
___ 30
___ 4
___ 8
___ 17
___ 90
___ 15
___ 24
___ 82

Post-test: Task 3: Assessing magnitude of numbers 1-100

Explain the child to circle with a pencil the bigger number from both numbers. Demonstrate one question.

The script: “This is the last game. Which number is bigger 25 or 12, I’m making a circle around the number that is bigger, I think that 25 is bigger than 12, now you can do the next one”.
25 or 12
72 or 11
97 or 77
89 or 12
93 or 83
10 or 41
55 or 58
35 or 67
41 or 63
6 or 23
12 or 15

*Please thank the child and give him the third sticker.
APPENDIX B: Script for testers of Touch-Non-Congruent Gestures condition (including only the intervention section that is different from Appendix A)

INTERVENTION (computer games):

1. NUMBER LINE TASK (max 20 min)

Children will be required to estimate 23 numbers (1-100) on a virtual number line. The computer will narrate the questions so children will not need to recognize the symbols. Prior to the task, the experimenter will explain what is a number line and ask the child to show her if there is zero on the number line and if there is the number one hundred, to make sure the child recognizes the numbers.

*The experimenter will enter the subject’s number and the child’s first and last name to the log on box.

The Script: “This is a number line. A number line is a line with numbers across it. The numbers on the line go from the smallest number to the largest number and the numbers go in order. Each number has its very own spot on the number line. The experimenter will demonstrate one question and will allow the child to try out another question: “where is the number 95? I believe it is here (The experimenter will tap with his finger on the number 95 on the number line bar and then tap on the done button), you can go back and forth but once you press the “done” button you can’t change your answer. Now you can try, where is the number 90? Good, now press the done button”

*The experimenter will mark the strategies that the child use (on the strategies page) for each question.

2. COUNTING AND ADDITION TASK (max 20 min)

Children will be required to solve ten additions problems by working on a virtual manipulative interface, that shows virtual blocks arranged in side by side piles of two 10 block towers. The addition problems will range from 1-20, such as, 6+7=? 2+9=?

The computer will narrate the questions so children will not need to recognize the symbols. The experimenter will demonstrate one question on the computer (3+4=?) and will allow training of the second question (2+1=?).
*The experimenter will enter the child’s first and last name to the log on box

*The script: “This is a blocks game, you need to figure out how many blocks are in the left and right piles. For example, how much does 3 and 4 make together? (The experimenter will tap with his finger on the number 3 below the left pile and on the number 4 below the right pile. Then, he will tap on the answer 7 below), 3 and 4 makes 7 together, so I press the number 7 on the green button, now it’s your turn to try the next one. Remember that you only have one trial for each question and that you have to click on the numbers below each columns before you answer”

*The experimenter will mark the strategies that the child uses (on the strategies page) for each question.
APPENDIX C: Script for testers of Mouse-Congruent Gestures condition (including only the intervention section that is different from Appendix A)

INTERVENTION (computer games):

1. NUMBER LINE TASK (max 20 min)

Children will be required to estimate 23 numbers (1-100) on a virtual number line. The computer will narrate the questions so children will not need to recognize the symbols. Prior to the task, the experimenter will explain what is a number line and ask the child to show her if there is zero on the number-line and if there is the number one hundred, to make sure the child recognizes the numbers.

*The experimenter will enter the subject’s number and the child’s first and last name to the log on box.

The Script: “This is a number line. A number line is a line with numbers across it. The numbers on the line go from the smallest number to the largest number and the numbers go in order. Each number has its very own spot on the number line. The experimenter will demonstrate one question and will allow the child to try out another question: “where is the number 95? I believe it is here (he will drag the mouse forward to number 95 and then click the done button), you can go back and forth but once you press the “done” button you can’t change your answer. Now you can try, where is the number 90? Good, now click the done button”

*The experimenter will mark the strategies that the child use (on the strategies page) for each question.

2. COUNTING AND ADDITION TASK (max 20 min)

Children will be required to solve ten additions problems by working on a virtual manipulative interface, that shows virtual blocks arranged in side by side piles of two 10 block towers. The addition problems will range from 1-20, such as, 6+7=? 2+9=?

The computer will narrate the questions so children will not need to recognize the symbols. The experimenter will demonstrate one question on the computer (3+4=? ) and will allow training of the second question (2+1=?).

*The experimenter will enter the child’s first and last name to the log on box
*The script: “This is a blocks game, you need to figure out how many blocks are in the left and right piles. For example, how much does 3 plus 4 makes together? (The experimenter will click on each block to highlight the blocks color in each column), 3 and 4 makes 7 together, so I press the number 7 on the green button, now it’s your turn to try the next one. Remember that you only have two trials for each questions and that you have to click on the blocks before you answer”

*The experimenter will mark the strategies that the child uses (on the strategies page) for each question.
APPENDIX D: Script for testers of Mouse-Non-Congruent Gestures condition (including only the intervention section that is different from Appendix A)

INTERVENTION (computer games):

1. NUMBER LINE TASK (max 20 min)

Children will be required to estimate 23 numbers (1-100) on a virtual number line. The computer will narrate the questions so children will not need to recognize the symbols. Prior to the task, the experimenter will explain what is a number line and ask the child to show her if there is zero on the number-line and if there is the number one hundred, to make sure the child recognizes the numbers.

*The experimenter will enter the subject’s number and the child’s first and last name to the log on box.

The Script: “This is a number line. A number line is a line with numbers across it. The numbers on the line go from the smallest number to the largest number and the numbers go in order. Each number has its very own spot on the number line. The experimenter will demonstrate one question and will allow the child to try out another question: “where is the number 95? I believe it is here (he will click with the mouse on about 95 on the number line and then click the done button), you can go back and forth but once you press the “done” button you can’t change your answer. Now you can try, where is the number 90? Good, now click the done button”

*The experimenter will mark the strategies that the child use (on the strategies page) for each question.

2. COUNTING AND ADDITION TASK (max 20 min)

Children will be required to solve ten additions problems by working on a virtual manipulative interface, that shows virtual blocks arranged in side by side piles of two 10 block towers. The addition problems will range from 1-20, such as, 6+7=? 2+9=?

The computer will narrate the questions so children will not need to recognize the symbols. The experimenter will demonstrate one question on the computer (3+4=?) and will allow training of the second question (2+1=?).
*The experimenter will enter the child’s first and last name to the log on box

*The script: “This is a blocks game, you need to figure out how many blocks are in the left and right piles. For example, how much does 3 plus 4 makes together? (The experimenter will click on the number below each column to highlight the blocks), 3 and 4 makes 7 together, so I press the number 7 on the green button, now it’s your turn to try the next one. Remember that you only have one trial for each question and that you have to click on the numbers below each columns before you answer”

*The experimenter will mark the strategies that the child uses (on the strategies page) for each question.
APPENDIX E: Letter of Consent form for Experiment 2

Teachers College, Columbia University

INFORMED CONSENT

DESCRIPTION OF THE RESEARCH: My name is Ayelet Segal and I’m a doctoral student at Teachers College, Columbia University. I would like to invite your child to participate in my dissertation study examining young children’s interaction with different digital devices to better learn mathematical concepts. Other graduate students and I will conduct this study during after school program hours in your child’s classroom. My advisor, Dr. John Black, will oversee this research study. Participating children will first be given five short paper and pencil tests to measure their math skills. Then, each child will be randomly assigned to one of four groups that will individually work on a digital device (computer or an iPad) to solve two mathematical tasks. One task involves counting and adding numbers 1-20 and the other task is estimating number on a number line 1-100. Then, children will be given another five short paper and pencil tests to measure their math skills. The child will be videotaped while solving the testes and tasks. These videotapes will be transcribed and analyzed for use in my dissertation. Portion of the videos may be shown at scientific meetings or used for educational purposes. Children who will get to solve the problems only with the computer and would like to also interact with the iPad will be allowed to do so after completing their first session with the computer.

RISKS AND BENEFITS: Children will encounter the same amount of risk participating in this research study as they would during a typical classroom activity. Children who do not wish to participate in the study will participate in normal classroom activities. If your child decides that he or she does not want to participate, he or she will be removed from the study.

DATA STORAGE TO PROTECT CONFIDENTIALITY: Once all information is collected each child, teacher, and school will be given a pseudonym. All data referring to children, teachers, and schools will use these pseudonyms. Video clips of children will only be identified by children’s pseudonyms. I will store all data in locked filing cabinets in my school or home office.

TIME INVOLVEMENT: Overall, your child’s participation will take approximately 1 session of 50 minutes over the span of three months. (testing at the beginning and end will take 20 minutes in total, the tasks will take 30 minutes in total). Therefore,
participants will miss about 50 minutes of their after school program activity during
the semester.

HOW WILL RESULTS BE USED: The results of the study will be primarily used for my
dissertation. These results may also be published in journals and articles or
presented at scientific meetings. Your school will also receive a copy of the results.
Since all children, teachers, and schools will be given pseudonyms, there will be no
way to identify our children in the publication of this research data. Videos of your
children, identified by their pseudonyms, may also be shown during scientific
meetings or used for educational purposes.

To give your consent, please read and sign the Participants’ rights section and return
the form to your child’s teacher.

Teachers College, Columbia University PARTICIPANT'S RIGHTS
Principal Investigator: __Ayelet Segal

___________________________________________________________
Principal Investigator: __

Research Title: __ Utilizing gestural interfaces for certain learning supports
better performance: Comparing levels of direct manipulation with
manipulatives

• I have read and discussed the Research Description with the researcher. I have
had the opportunity to ask questions about the purposes and procedures regarding
this study.

• My child’s participation in research is voluntary. He or she may refuse to
participate or withdraw from participation at any time without jeopardy to future
medical care, employment, student status or other entitlements.

• The researcher may withdraw my child from the research at her professional
discretion.

• If, during the course of the study, significant new information that has been
developed becomes available which may relate to my child’s willingness to continue
to participate, the investigator will provide this information to me.

• Any information derived from the research project that personally identifies my
child will not be voluntarily released or disclosed without my separate consent,
except as specifically required by law.

• If at any time I have any questions regarding the research or my child’s
participation, I can contact the investigator, who will answer my questions. The
investigator's phone number is (917)2260559.
• If at any time I have comments, or concerns regarding the conduct of the research or questions about my child’s rights as a research subject, I should contact the Teachers College, Columbia University Institutional Review Board /IRB. The phone number for the IRB is (212) 678-4105. Or, I can write to the IRB at Teachers College, Columbia University, 525 W. 120th Street, New York, NY, 10027, Box 151.
• I should receive a copy of the Research Description and this Participant’s Rights document.
• Since videotaping is part of this research,
  1. I ( ) consent to be audio/video taped.
  2. I ( ) do NOT consent to being video/audio taped. The written, video and/or audio taped materials will be viewed only by the principal investigator and members of the research team.
• Written and videotaped materials
  1. ( ) may be viewed in an educational setting outside the research
  2. ( ) may NOT be viewed in an educational setting outside the research. • My signature means that I agree to my child participate in this study.
Child’s name: ________________________________ Gender: Male/Female Child’s date of birth: _____/_____/______
Guardian's Signature/consent: ________________________________
Date:____/____/____
Guardian's Name: ________________________________
Teachers College, Columbia University
Investigator's Verification of Explanation
I certify that I have carefully explained the purpose and nature of this research to ________________________________ (participant’s name) in age-appropriate language. He/She has had the opportunity to discuss it with me in detail. I have answered all his/her questions and he/she provided the affirmative agreement (i.e. assent) to participate in this research.
Investigator’s Signature: ________________________________ Date: ________________________________