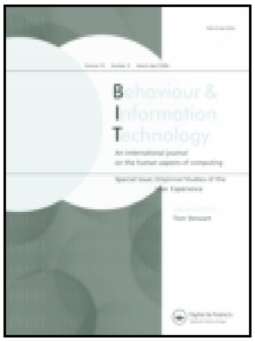

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Exploring how children use their hands to think: an embodied interactional analysis

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In order to better understand how to design hands-on child-computer interaction, we explore how different styles of interaction facilitate children's thinking while they use their hands to manipulate objects. We present an exploratory study of children solving a spatial puzzle task. We investigate how the affordances of physical, graphical and tangible interfaces may facilitate the development of thinking skills including mental visualisation, problem space exploration and collaboration. We utilise the theory of complementary actions taken from embodied cognition to develop a video coding methodology that allows us to classify behavioural activity and make inferences about thinking skills development. Our findings indicated that the combination of direct hands-on input style with audio-visual feedback facilitated by the tangible user interface enabled a dynamic task completion strategy, which supports the development of mental skills with a slight time cost. The mouse and graphical user interface supported a trial and error approach, which may limit skills development. The physical cardboard puzzle enabled effective task completion but provided less support for social interaction and problem space exploration. We conclude with design recommendations.

Keywords: children; tangible user interfaces; hands-on interaction; embodied interaction; complementary actions; epistemic actions; problem solving; spatial puzzle solving; user interface; cognition; comparative study

1. Introduction

Tangible user interfaces (TUIs) are progressively moving out of the research lab and into the physical and social environments of children's everyday lives. TUIs are user interfaces those utilise physical artefacts as representations and controls for digital information (Ullmer and Ishii 2000). A key characteristic is the seamless integration of representation and control. The attributes of physical artefacts represent information (e.g. size, shape, colour), and are used to control, through direct manipulation, associated digital representations. The exploration of the benefits of TUIs and associated interaction styles for adult users has received much research attention (Forlines *et al.* 2007, Brandl *et al.* 2008). Studies that aim to understand the benefits of TUIs for children and learning are emerging but not conclusive (e.g. Harris *et al.* 2004, Fails *et al.* 2005, Fernaeus and Tholander 2006, Marshall 2007, Price *et al.* 2008). There are still no general guidelines for when and how to implement TUIs for classes of children's learning activities. In addition, studies that focus on input methods with child users have focused mainly on analysis of factors related to mouse use (e.g. Hourcade *et al.* 2007, Moraveji *et al.* 2009). While proponents of hands-on learning for children have turned their attention to TUIs (e.g. Resnick *et al.* 1998, Zuckerman *et al.* 2005), investigations that explore and compare interactional behaviours and underlying cognitive mechanisms for claimed benefits are only just emerging (e.g. Bakker *et al.* 2009). What is needed are studies that explore the same task implemented with different interaction styles in order to better understand how each user interface style facilitates the development of specific skills and knowledge through motor-cognitive processes. We present an exploratory comparison of physical, graphical and TUI in order to identify interactional patterns that are facilitated by the specifics of each interface style. Our contributions are preliminary findings about how each style of interface supports hands-on interaction and resultant development of mental skills related to spatial problem solving.

One theoretical perspective that is important for understanding a hands-on approach to child–computer interaction is embodied cognition (Dourish 2001). Despite a history in human computer interaction dating back to Winograd and Flores' early work (Winograd and Flores 1986), studies that actively incorporate an embodied approach to interaction in their theoretical underpinnings are rare. Human physical bodies play a central role in shaping human interactions and experience *in* the world and resulting understanding *of* the world (Johnson 1987). Recent

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studies have shown the integral role that human hands play in communication, memory and thinking (Goldin-Meadow 2005). Much of this work has yet to be integrated explicitly into research that investigates child-computer interaction. We ground our investigation of children's hands-on interaction patterns in understandings of the motor-cognitive mechanisms, which may underlie learning through direct physical interaction with the environment. We use notions from embodied cognition as a theoretical lens that helps us explore, understand and interpret children's hands-based behaviours during a spatial problem solving task.

Understanding the opportunities and challenges of hands-on child-computer interaction requires not only empirical work but also new methodologies. Traditional usability measures of task time and completion rates and user experience measures based on surveys and interviews are not be sufficient to understand how interface elements affect underlying motor-cognitive processes. In order to understand the role that the hands play in thinking during interaction, we need ways to classify and code hand-based behaviours. This enables us to relate hands-on behaviours to task performance and make inferences about resultant mental skills development. We have developed a video analysis methodology based on an embodied perspective on cognition. Specifically, we used the theory of complementary actions to develop hands-based event classes. We classified hand actions based on the role or function that object manipulation plays in problem solving. We then quantised hand-based events to understand the average duration and frequency for each class of hand action. We also examined temporal sequences of events to understand how interactional patterns change through problem solving sessions. Since children use their hands directly on objects in TUIs and through a mouse in traditional interfaces, we developed an approach that is suitable for studying both direct hands-on and indirect mouse-based input methods.

Using this methodology, we investigated, in detail, the similarities and differences in children's interactional patterns that arose when they used different interface styles to solve the same spatial task. Our research goal was to better understand the mechanisms and benefits of different forms of interaction and to work towards generating guidelines that suggest when each form of interaction may be beneficial. In a previous short article, we reported that no significant differences were found on measures of enjoyment and engagement between three user interface styles (i.e. physical, graphical and tangible) (Xie *et al.* 2008). In another article, we reported our preliminary results of a comparison of measures of hands-on event durations (Antle *et al.* 2009a). In this longer article, we extend previous work by providing the details of our video analysis methodology; presenting additional quantitative measures and findings; detailing our temporal analysis of interactional patterns; and by discussing the implications of all of these findings for designing hands-on child-computer interaction that supports the development of thinking skills.

2. Related work

This section briefly summarises the history of claimed benefits of children's hands-on learning; summarises several recent studies comparing TUIs with other styles of interaction; and provides an overview of our exploratory research questions that are related to the effects of hands-on interaction styles on the development of thinking skills.

2.1. Children and hands-on interaction with the world

Direct physical interaction with the world is a key component of cognitive development in childhood. Piaget began a long tradition of thought that suggests that cognitive structuring through schemata accommodation and assimilation requires both physical and mental actions (Piaget 1952). Historically, Friedrich Froebel (Brosterman 1997) and Maria Montessori (Montessori 1966) are credited with popularising hands-on approaches to learning that involve the manipulation of physical materials. Manipulatives are educational materials that are designed in a way that some aspect of their physical form represents abstract concepts.

A substantial body of work by educational theorists, cognitive scientists and gesture researchers supports the assertion that our hands play an integral and critical role in the development of thinking skills (Klemmer *et al.* 2006). Goldin-Meadow suggests that gestures serve both communicative and thinking processes (2005). She summarises research that provides evidence that people use gestures more when doing difficult tasks. This not only reflects the cognitive effort they are expending but it is also a way that they reduce cognitive load. The mechanisms at work here remain to be fully investigated. Gestures may lighten the cognitive load because they are a motor act; because they help people link words to the world (e.g. deictic gestures); or because they help a person organise spatial information into speech (e.g. iconic or metaphoric gestures) (Goldin-Meadow 2005). Other studies suggest that various cognitive operations (e.g. spatial memory, lexical retrieval) are degraded when the use of the hands is prevented (Morsella and Krauss 2004).

Recently, the manipulative approach has been extended to computational domains (e.g. Montemayor *et al.* 2002, Price *et al.* 2003, Lamberty and Kolodner 2004). Proponents of this approach claim that the role of hands-on actions on physical computational objects can make abstract concepts more accessible to children (Resnick 2006). Less widely appreciated is the value of actions that can simplify mental tasks that do not involve abstract concepts or symbolic representations (Kirsh 1995). For children, theory suggests that supporting physical actions on computational objects makes difficult mental thinking tasks easier to perform and thus is beneficial. This should be particularly relevant for tasks involving the tight coupling of mental and physical operations. Computation can also provide feedback on the effects of action, which may not be possible to achieve in non-computational environments.

2.2. *Input and interaction studies*

There has been considerable research comparing various aspects of input devices for adults (Forlines *et al.* 2007). While researchers have studied bimanual interaction (see Brandl *et al.* 2008 for a review), few have compared mouse-based and tangible interaction styles. A notable exception is Fitzmaurice *et al.* who conceptualised the difference between input using a mouse and tangible objects as time or space multiplexed (Fitzmaurice *et al.* 1995). Time multiplexed input uses one input device to control different digital representations (or functions) at different points in time (e.g. mouse, stylus). The device is repeatedly attached to and dettached from various digital objects that comprise the graphical user interface (GUI). In contrast, space multiplexed input involves dedicated input devices where each digital representation (or function) has a dedicated transducer. A space multiplexed style of input affords the ability to take advantage of the shape, size and other physical and spatial qualities of multiple physical controllers to increase functionality and decrease complexity. Fitzmaurice *et al.* suggested that users would perform better on a tracking pursuit task using space multiplexed input devices compared to using time multiplexed devices. They found evidence to support notions that space multiplexed input devices are easier and faster to acquire than the corresponding virtual handlers in the time multiplexed group; that concurrent access afforded by space multiplexing provides performance benefits; that the specialised form factor of space multiplexed devices reminds users which virtual handler they were attached to and also facilitates appropriate manipulation. While Fitzmaurice *et al.*'s study focused on task performance with adult participants, it was one of the few input studies than compared time and space multiplexed devices. Further study is needed to determine if Fitzmaurice *et al.*'s findings generalise to children who have less developed motor-cognitive skills (e.g. manual dexterity).

Studies of input methods for children have tended to focus on mouse-based interaction (e.g. Inkpen *et al.* 1999, Hourcade *et al.* 2007). A recent study found that using multiple mice (up to 32!) on a large shared display did not degrade performance as long as targets were not small (Moraveji *et al.* 2009). Tasks involved were pointing and selecting, and text entry. However, the study did not examine the different strategies or behaviours that multiple mice afforded. Fails *et al.* made a step towards explaining differences in physical and graphical interfaces that support children's learning of hazards through a comparative study with pre-school aged children (Fails *et al.* 2005). However, they found it difficult to quantitatively measure differences in learning that were related to input and interface style. Qualitative findings supported claimed TUI benefits of active engagement and participation.

To the best of our knowledge, no research has investigated and compared the benefits of tangible, physical and mouse-based interaction styles for children's spatial problem solving tasks or other forms of object manipulation tasks that may support the development of thinking skills through hands-on child-computer interaction.

2.3. *Research goal: exploring interaction styles*

There are many open questions about the inter-relation between input elements of different interface styles, children's interactional behaviours, and the development of children's thinking skills. We focus on thinking skills related to a spatial problem solving activity that requires manipulation of objects or pieces (e.g. spatial puzzles). Spatial puzzles may facilitate the development of children's spatial thinking and problem solving skills including mental visualisation, spatial reasoning, metacognition (e.g. problem space exploration) and, if done in groups, communication skills related to collaborative or cooperative problem solving. To explore how different child-computer interaction styles facilitate the development of these skills, we compare three interface styles: physical (i.e. non-computational), mouse-based (traditional GUI) and TUI.

We address the following exploratory questions in this article:

- What are the main similarities and differences in interaction patterns between manipulating

physical objects with the hands and manipulating digital representations of those objects with a mouse during a spatial task?
- How does each interaction style support or constrain successful spatial task completion?
- How does each interaction style support or constrain the development of thinking skills?
- How does each interaction style support or constrain the communication between pairs working together on puzzles?

While we cannot elicit explicit evidence that identifies the development of specific mental skills (e.g. visualisation, spatial reasoning), we can make inferences from behavioural data to better understand the strengths and weaknesses of each interaction style in terms of supporting skills development. We summarise our findings in order to provide information to guide designers to make informed choices about hands-on child-computer interaction.

3. Theory: thinking with and through the hands

Addressing our research questions requires a theoretical framework that explicates the motor–cognitive mechanisms underlying hands-on spatial problem solving. Theories from an embodied perspective on cognition are appropriate to explore motor-cognitive mechanisms. In this section, we begin by describing the role or function that handling objects plays in children's thinking with and through those objects. We then describe different kinds of hand actions using notions from the theory of *complementary actions* to help us understand the mechanisms and benefits of children using their hands to directly manipulate objects in problem solving. We then analyse a spatial problem solving task (jigsaw puzzle) in order to understand how these different kinds of hands-on manipulations of objects are used during the task. Taken together, this section forms the theoretical basis for our methodology of embodied interactional analysis and helps us interpret our findings.

3.1. Object manipulation

Physical objects can be manipulated directly with the hands or indirectly with tools. Similarly, computational objects can be manipulated directly using the hands (e.g. tangibles) or indirectly using a mouse (or other input device). These types of hand actions on objects may serve several different functions as follows. For the purposes of example and to demonstrate how these mechanisms are apparent in early child development, we will use a child and a block shape sorting box as shown in Figure 1.

Figure 1. Block shape sorting box.

A child may use his/her hands to manipulate an object to directly move that object to a location or orientation that they already have in mind. For example, a child may put a square block in the square hole. Or a child may use their hands to manipulate an object to determine where it will fit. For example, a child may manipulate a square block in order to see if it fits in a particular hole by trying to push it through. The result of this may be that the object fits and is pushed through or it may not fit and then another hole may be tried or it may be put back down. A child may also move an object simply to *explore* it. For example, a child may pick up and play with various blocks without trying to push any of them into the box.

In each case, manipulating the object serves a different function that a child may or may not be aware of. Notions from the embodied cognition theory of complementary actions can be used to explicate the different functions of object manipulation in spatial problem solving as described in the following two sections.

3.2. The theory of complementary actions

3.2.1. Complementary actions

An individual or group of individuals can improve their cognitive strategies for solving a problem by adapting the environment. One of the ways individuals do this is through complementary strategy. Kirsh defines a complementary strategy as any organising activity that recruits external elements to reduce cognitive loads (Kirsh 1995). A complementary action can be recognised as an interleaved sequence of mental and physical actions that results in a problem being solved in a more efficient way than if only mental or physical operations had been used. The external elements may be fingers or hands, pencil and paper, stickies, counters, or other entities in the immediate environment. Typical organising activities include arranging the position and orientation of objects, pointing, manipulating counters, rulers or other artefacts that can encode information through manipulation. Complementary strategies involve either pragmatic or epistemic actions as described in the next section.

3.2.2. *Epistemic and pragmatic actions*

Individuals can use *epistemic* actions to lighten mental work. Epistemic actions are those actions used to change the world in order to simplify the problem-solving task. This is often subtly misstated or misinterpreted as manipulating something in a task to better understand its context. However, the defining feature of an *epistemic* action is that the action changes the world in some way that makes the task easier to solve. The classic example involves a user manipulating pieces in the computer game Tetris; not to solve the task at hand but to better understand how rotated pieces look (Kirsh and Maglio 1994). A physical action transforms the difficult task of mentally visualising possible rotations and offloads it to the world, making it a perceptual-motor task of physically rotating pieces in order to make the subsequent play of the game easier. In this case, actions are not directly related to solving the current falling pieces in Tetris but instead are related to make it easier to understand how pieces look when they are rotated in general so subsequent game play is easier. In contrast, *pragmatic* actions are those actions whose primary function is to bring the individual closer to his or her physical goal (e.g. winning the game, solving the puzzle).

3.3. *Prototypical spatial problem solving activity*

A jigsaw puzzle is a spatial problem solving activity that is traditionally solved by one or more players using a combination of single and two handed manipulation of physical objects. From an embodied cognition perspective, a jigsaw puzzle is a prototypical activity that requires complementary actions to successfully solve it. That is, solving it requires the combination of purely internal mental operations with physical operations on objects (Clark 1997, Kirsh 1999).

Object manipulation may serve three intertwined roles in jigsaw puzzle solving. First, players may manipulate pieces simply to move pieces into their correct positions that they already know. We call these *direct placement actions*. They are pragmatic but do not involve complementary actions. Like the child who knows the square block fits in the square hole, the function of object manipulation is simply to directly place the object. Second, players may manipulate pieces in order to determine their correct placement. These are complementary actions because manipulating the pieces makes the mental operations of visual search, image visualisation and/or spatial rotation easier to perform by offloading part of each mental operation to physical action in the environment (Kirsh 1995). Complementary actions are often part of a trial and error approach to visual search. Since these actions result in correct placement, their function is also pragmatic. We call these *indirect placement actions*. Third, players may manipulate pieces in order to explore the problem space. They may do this in two ways, which are difficult to distinguish from observational data. Players may seem to randomly manipulate or ‘play’ with pieces. They may do this as part of exploration but with no apparent goal in mind, or they may do this with goals that become apparent over time. For example, over time they may organise puzzle pieces into groups (e.g. corner pieces, edge pieces, pieces of the same colour). In each case, these intermediate steps support later visual search. The function of the actions is epistemic because they involve manipulating pieces in order to simplify the task of solving the puzzle. Neither the seemingly random explorations nor these purposeful actions are pragmatic because neither type of action involves placing a piece in its correct location (Kirsh 1999). We call both these kinds of actions *exploratory actions* because they both serve exploratory functions. Table 1 summarises these classes of hands-on action types.

Although a puzzle can be solved through physical, tangible or mouse-based interaction, these approaches are not cognitively equivalent. Directly manipulating a puzzle piece with the hands involves acquiring the piece, and manipulating it. The TUI adds responsive audio and visual feedback to guide action. Using a mouse involves acquiring the mouse, using the mouse to acquire the digital puzzle piece, which requires coordination between the input space and display space, and manipulating the digital puzzle piece. Like the TUI, mouse-based interaction also provides audio and visual feedback.

4. Methodology: study design

In this section, we describe our research study design. In the following section, we provide details of our methodological approach, which involves coding, quantifying and analysing the behavioural video data of children’s hand actions during puzzle solving.

Table 1. Action types based on embodied cognition.

Action type	Direct	Complementary	Pragmatic	Epistemic
Direct placement	Yes	No	Yes	No
Indirect placement	No	Yes	Yes	No
Exploratory – random	No	Yes	No	?
Exploratory – epistemic	No	Yes	No	yes

4.1. *Study design*

In order to explore the similarities and differences in the three interaction styles, we designed a study involving school-aged children solving jigsaw puzzles. We included three interface styles for the same puzzle: physical user interface to a cardboard puzzle (PUI), traditional mouse-based GUI puzzle and TUI puzzle.

There are several factors that vary with each user interface implementation. Key differences between the PUI, GUI and TUI puzzle implementations are shown in Table 2. The main differences in interface styles are related to directness, tangibility, spatiality and computation. A TUI affords direct, space multiplexed interaction with tangible objects in 3D space and provides digital feedback on a horizontal surface. A PUI affords direct interaction with physical objects in 3D space but provides no digital feedback. A GUI affords indirect, time multiplexed interaction with digital objects in 2D space and provides digital feedback on a vertical surface.

Pairs of children were given the opportunity to play with the puzzle using only one interface style to avoid novelty effects seen in pilot studies. We used a paired group since jigsaw puzzles are commonly done by pairs of children and to elicit verbal data that might provide insight into mental processes.

4.2. *Materials: the puzzles*

All puzzle implementations used one of two different content themes, each with the same modern style of cartoon illustration. One theme was a whimsical illustration of an imaginary castle with bats, ghosts, witches, knights and a princess. The other theme was an illustration of the legendary pirate Barbarossa and his ship, the Black Pearl. Both themes are inclusive of gender and are currently popular in children's media as can be seen in the success of Harry Potter and the Pirates of the Caribbean books and movies.

4.2.1. *Physical user interface*

The PUI style cardboard jigsaw puzzles chosen for the study were designed and manufactured by DJECO. Each puzzle consisted of 54 pieces (6 × 9). Each puzzle came with a poster of the image, which we used as the underlay for the puzzle. This provides visual guidance for puzzle placement comparable to the digital images used in the two computational puzzle implementations.

Table 2. Differences in implementation features.

	PUI	GUI	TUI
Space multiplexed input	N/A	−	+
Time multiplexed input	N/A	+	−
Really direct interaction	+	−	+
Multi-user/multi-hand	+	−	+
Horizontal display	+	−	+
Audio & visual feedback	−	+	+
Tactile feedback	+	−	+
Integration of I/O space	+	−	+

4.2.2. *Mouse and graphical user interface*

The mouse-GUI style puzzles were created using commercially available jigsaw puzzle creation software developed by TIBO software. The input style of a mouse is time multiplexed (Fitzmaurice *et al.* 1995). The puzzle pieces could be manipulated by using drag-and-drop manipulation, and each could be rotated by simultaneously right-clicking the mouse. Users could either show or hide a real size reference picture in the background (see Figure 2, left). When pieces were correctly connected, they were connected permanently. Visual and audio feedback was provided by the software for correct matches. Visual feedback involved changing the transparency of the image on the pieces of correct matches. Audio feedback involved a 'click' sound for correct connections.

4.2.3. *Tangible user interface*

The TUI puzzles were implemented on the EventTable tabletop prototype described in (Antle *et al.* 2009b) and shown in Figure 2, right. The tangible puzzle pieces were space multiplexed input devices (Fitzmaurice *et al.* 1995). In response to input events, a logic programme was used to control visual and audio feedback similar to the GUI feedback. The final prototype was a tangible interface to the physical

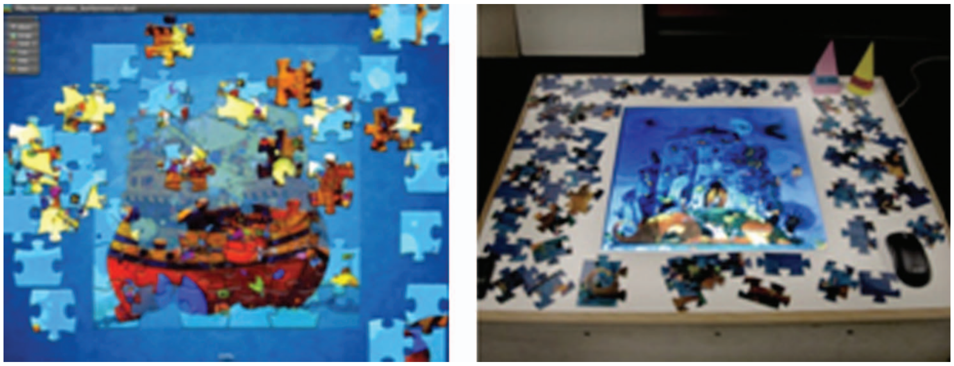

Figure 2. Mouse-GUI (left) and TUI (right) puzzles.

jigsaw puzzle that embodied the properties and functions of both the PUI and mouse-GUI.

4.3. *Participants and procedure*

We recruited 132 children aged 7–10 years old (69 boys and 63 girls) from the regular visitor population of a local science centre over a four week period. Children were randomly assigned to conditions. Of these children we focused on 40 children for the video analysis. These sessions were chosen because they had minimal occlusion of player hand actions by player bodies. Ninety per cent of all participants had played jigsaw puzzle before, and all participants knew how to solve jigsaw puzzles. All participants had used personal computers, and 92% of them considered themselves as good mouse users.

Each session was held in a laboratory space at the science centre. Pairs of children were shown one puzzle implementation and asked to solve the jigsaw puzzle together as many times as they liked. Each pair was told they would have 15 minutes to play with the puzzle. They were told that they could stop playing the puzzle at any time and instead move to an area with benches, pillows and a collection of popular children's books that served as viable alternative activity.

4.4. *Data collection*

This study design facilitated the collection of several forms of quantitative and qualitative data. In this article, we focus on the video data of the first puzzle completion segment of 20 sessions (with 40 children). We analysed four PUI, eight GUI and eight TUI sessions.

4.5. *Limitations of study design*

The comparison of mouse- GUI, PUI and TUI facilitated the exploration of the similarities and differences between the interaction styles. Our goal was to produce guidelines for designers of hands-on learning and play materials. We included a traditional non-computational puzzle as a baseline. This enabled us to explore the benefits of adding computational elements to traditional materials. We included a single mouse interface since this style of input is by far the most frequent configuration found in children's classrooms, museums, libraries and homes. Dual mice are relatively rare and not supported by most software applications. We included a tangible tabletop because interactive surfaces are becoming commercially available (e.g. MS Surface, Entertainable, Smart Table) and include children (i.e. schools and museums) in their target markets.

There are other configurations we might have studied (e.g. multi-touch tabletop). However, our three choices included three dominant interaction styles that are suitable for hands-on learning. The differences in implementations limit the strength of any scientific claims we can make based on our findings. However, our findings can provide valuable information that will enable designers to make informed decisions about which interaction style to use for the design of a particular children's interactive learning product or system.

5. Methodology: embodied interactional analysis

We use a theoretically based methodology for the coding and quantising of hand action events in puzzle solving. Our methodology includes definitions of classes of behavioural events derived from the roles that hand actions play in thinking.

5.1. *Classification of observable behavioural events*

For a child solving a jigsaw puzzle, we have identified several kinds of observable behavioural events. Each type of event can occur using the mouse to manipulate a digital puzzle piece or using the hands to directly act on a physical puzzle piece.

Children's behaviours in video segments can be coded using an event based on a unit of analysis called a 'touch'. A *touch event* begins when a puzzle piece is first 'touched' (by cursor or hand) and ends when the piece is 'let go'. In all interaction groups, we confined our analysis scheme to the dominant hand because we observed that the non-dominant hand in the physical and tangible groups usually provided a supporting role. We did not observe users simultaneously but independently placing two pieces, one with each hand.

Based on the roles of object manipulation summarised above in Table 1, we used three classes of touch events: direct placement, indirect placement and exploratory action as follows. A *direct placement* touch event occurs when manipulation only serves to orient the piece to the correct location. We can visually identify a direct placement event when a child picks up a specific piece and immediately places it, often with the hands directly following eye gaze. There is no hesitation.

An *indirect placement* touch event occurs when a child manipulates the piece in order to determine where it fits and then places it. In this case, physical manipulation serves to offload some portion of mental operation to physical action. A prototypical example is when a child picks up or selects a random piece and moves the piece across the display, visually comparing it to the puzzle image in order to see where it might fit using a trial and error approach. Indirect placements involve pragmatic complementary actions.

An *exploratory action* touch event is when a child touches or moves a piece but does not place the piece correctly in the puzzle. A prototypical example is when a child organises edge pieces by placing them in a pile. Exploratory actions involve complementary actions and may be epistemic.

We also included non-touch but still on task events and off-task events into our coding scheme. Non-touch but on task events were largely communicative in nature (e.g. verbal or gestural communication related to the task). For this reason we abbreviate them as *communication* events.

This coding scheme is mutually exclusive. The three classes of touch events (i.e. direct, indirect and exploratory) combined with the communication and off-task classes constituted all observed behaviours. Video was coded using Noldus Observer version 8.1. Each session was coded twice, once for each child participant (40 children). Video examples of each action event class can be found at www.antle.iat.sfu.ca/Physicality/ThinkingWithHands. Inter-rater reliability was achieved by successive iterations of group coding followed by pair coding and comparisons of individual coding by two trained coders until reliability of over 95% was achieved. The principle investigator helped refine coding rules, reviewed a subset of coded sessions and helped resolve discrepancies identified by or between the two coders.

5.2. *Absolute measures*

Based on coding of the five event classes described above, we used the Noldus analysis features and Microsoft Excel to calculate the following measures for each session.

5.2.1. *Performance measures*

(1) Mean puzzle completion time (time in minutes and seconds).
(2) Mean count of all events per session.
(3) Task completion (complete, quit, ran out of time).

5.2.2. *Absolute interaction behavioural measures*

(1) Absolute mean event class durations (time in minutes and seconds).
(2) Absolute mean event class frequencies (counts).
(3) Mean number of times a piece is handled.

5.3. *Relative measures*

We introduced relative measures to take in to account the single versus multiple input device difference between interaction groups. We created relative measures by calculating each event class mean as a proportion of the total duration or count for both children in a pair. We used two types of relative measures. First, we calculated relative measures of event classes given as a percentage of the session completion time or event count. For example, we calculate the *proportional event class duration* of direct placements relative to total completion time as the percentage of time that both children in a pair spend taking direct placement actions normalised by their total completion time. This tells us what proportion of the total time each child spent solving the puzzle was spent taking direct placement actions. Second, in order to better compare only manipulation event classes between interaction groups, we calculated proportional event class durations relative to manipulation time only (i.e. sum of direct, indirect and exploratory event times). For example, we calculated the proportion of event class duration spent in direct placement as the percentage of time that both children in a pair spend taking direct placement actions normalised by the total time they each spend actively manipulating pieces. This tells us what proportion of the time each child spent manipulating pieces was spent taking direct placement actions. See (Antle *et al.* 2009a) for more details on how relative measures are calculated. What is important is that these measures allow us to compare the three interaction groups in a way that accounts for the different amounts of access to input device(s) afforded by each configuration.

5.3.1. *Relative interaction behavioural measures*

1. Proportional event class duration (relative to completion time).
2. Proportional event class counts (relative to total count).
3. Proportional event class duration (relative to manipulation time only).
4. Proportional event class counts (relative to manipulation counts only).

5.4. Temporal analysis

We used lag sequential analysis (LSA) on event data in order to provide counts of the number of times that each of the two types of event classes occurred in sequence for each interaction group. For example, LSA allowed us to determine how many times a direct placement followed an exploratory action for each interaction style.

We also created visualisations of the temporal sequence of events for each participant. This enabled us to visually search for similarities and differences between pairs in an interaction group; between successful and unsuccessful pairs and between interaction groups. We validated some observed patterns with results from LSA. For example, when visual analysis suggested that two event classes often followed each other, LSA indicated if the frequency of this occurrence was more or less than frequencies of other sequences event classes.

6. Findings

6.1. Contextual observations

We first describe some of the observed effects of interface differences on interactional behaviours in order to provide context for the quantitative findings and subsequent discussion of detailed findings. While Table 2 summarises the main differences in interfaces, here we summarise some of the main differences in the way children *interact* with those interfaces and with each other as a result of differences in the interface styles.

First, each interface had a different form of feedback. In the PUI, although the image poster is present as a reference, there was no dynamic feedback. The GUI and TUI both had dynamic visual and auditory digital feedback on correct puzzle placement. The auditory feedback could be processed without action. In the GUI group, the visual feedback occurred when the pieces snapped into place. However, the visual feedback of the TUI required that pieces were lifted up to see that the reference image underneath had been modified. We refer to this behaviour as ‘peeking’.

Second, the TUI and PUI cardboard pieces had to be physically connected. This could be done with the pieces flat on the table, either with one or two hands, or in the air (3D space) with two hands. We observed that children did spend some time fiddling with connections. GUI placement required cognitive effort and dexterity in using the mouse (or touchpad) to acquire each digital puzzle piece and to subsequently rotate and translate it. However, little effort was required to place a piece in the correct location since pieces snapped into place. Conversely, for PUI, children were able to acquire, rotate and translate cardboard pieces with little effort and less precision, but connecting pieces required more effort.

Third, the physical pieces in the TUI and PUI puzzles supported bimanual interaction. We observed that children tended to use both hands, with one being dominant and the other acting in a supportive role (e.g. pushing pieces around in a pile while the dominant hand selected the desired piece). The GUI group used only their dominant hand.

Fourth, the TUI and PUI setup supported mobility. Children moved around the TUI and PUI tabletops. This enabled them to change their perspective on the puzzle and on the pieces, and change their spatial relationship to their partner. In the GUI group, the children sat side by side and may have switched seats but rarely moved around the vertical GUI display.

Fifth, observational notes revealed six primary exploratory activities: (1) simply handling or moving pieces with no apparent purpose (mainly TUI and PUI groups); (2) peeking under placed pieces to check feedback (mainly TUI group); (3) exploring how two pieces might be physically connected (TUI and PUI groups only); (4) looking for a placement for a piece but not placing it (i.e. returning it to the side); (5) sorting through pieces without organising them; and (6) sorting through pieces and organising them (e.g. making a pile of edge or patterned pieces).

Lastly, the single mouse invariably resulted in a dynamic where one child controlled the mouse and the other actively engaged through directive gesture and verbalisations. The multiple objects in the TUI and PUI supported a more parallel style of activity with some collaboration between children (Xie *et al.* 2008). Observational notes revealed three roles of communication: (1) communicating individual progress (‘Look, it fits here!’); (2) providing direction or assistance, which often combined verbal and deictic gesture (pointing – 'Put it there .. no . . . over by the boat'.) (mainly GUI); and (3) requesting help ('Do you see a piece with a pirate head?').

6.2. *Summary of quantitative results*

Our video coding methodology allowed us to analyse event data in order to determine various measures. We summarise findings in term of absolute and relative measures, and LSA tables for each group. We use the PUI to provide a baseline but interpret results cautiously, since we only analysed four sessions (eight participants) for this group. We used descriptive rather than inferential statistics because of the exploratory nature of our work, and because our between-subject design resulted in a relatively small number of participants for each group. We highlight some table cells in grey to indicate results that we focus in section 7.

6.2.1. Performance

We begin with performance results since children must be able to work with and potentially solve puzzles to develop thinking skill. Table 3 gives the descriptive statistical results for the first completion time for each group. We note that the PUI mean for $n = 4$ is less than the mean reported in (Antle *et al.* 2009a) due to the reduced sample size as a result of hand occlusion in some sessions, and so we also provide the mean for $n = 8$ as reported in that article. We see that pairs were most quickly able to complete the puzzle in the PUI group, followed by the TUI and then by the GUI.

Table 4 gives the frequency analysis results for the number of events in each group. Pairs enacted almost twice as many actions in the TUI than the GUI group. Pairs in the PUI group took fewer total actions than the TUI group, which is consistent with the faster task time for PUI pairs, but requires further discussion since both PUI and TUI involve equivalent sets of input objects.

Table 3. Puzzle completion times: minimum, maximum, mean and standard deviation (minutes).

	Minimum	Maximum	Mean duration	Standard deviation
GUI	6:35	15:00	12:07	3:14
PUI (*n*=4)	7:35	10:44	8:51	1:27
PUI (*n*=8)	6:43	15:00	10:32	2:25
TUI	5:34	15:00	11:15	3:56

Table 4. Event class counts: minimum, maximum, mean and standard deviation.

	Minimum	Maximum	Mean event count	Standard deviation
GUI	48	130	100	27
PUI (*n*=4)	120	173	147	23
TUI	133	212	180	28

Table 5 gives the breakdown of how many pairs completed the puzzle, quit or ran out of time in each group. Pairs were most successfully able to complete the puzzle in the PUI group, followed by the TUI. No pairs quit working on the puzzle before the session time ran out in the PUI or TUI groups. We note that successful puzzle completion does not ensure skills development but may indicate already developed or newly developing skills.

6.2.2. Interaction events: absolute measures

We now move on to report findings about interaction events. Table 6 gives the absolute mean time both children in pairs spent in each event class for the three groups. The mean total time spent making direct placements is longest for PUI, a minute less for TUI, and two minutes less for GUI. The mean total time making indirect placements is about the same for GUI and PUI and almost half for TUI. Conversely, the mean total time spent taking exploratory actions is almost twice as long for TUI than either PUI or GUI.

Table 7 gives the absolute mean number of actions in each event class for the three groups. Pairs in the PUI and TUI groups took similar numbers of direct placements. Combining time and count results, we see that TUI pairs took far more exploratory actions. Although the time spent in communication was much longer for the GUI group (see Table 6), pairs had similar numbers of communications in the GUI and PUI groups, and *more* communication events in the TUI group.

Table 5. Task completion counts.

	Complete	Quit	Out of time
GUI	3	2	3
PUI	4	0	0
TUI	6	0	2

Table 6. Absolute mean event class durations (minutes).

	Direct	Indirect	Exploratory	Communication	Off task
GUI	2:13	4:26	4:50	18:11	1:19
PUI	4:07	4:12	5:45	2:56	0:11
TUI	3:12	2:29	9:58	6:10	0:38

Table 8 gives the average number of times each puzzle piece is handled or touched (i.e. acted on) for each group. TUI pieces are touched slightly more than PUI pieces and both are touched more than GUI pieces.

6.2.3. *Interaction events: relative measures for first completion*

We now provide summaries of relative measures, which enable a more equivalent comparison between interaction groups by focusing on the proportion of first completion time spent in each event type. Table 9 provides the proportions of time spent in each event class relative to the total first completion time. For the GUI group, of the total time spent on task, 7.3% was spent making direct placements, 15.1% making indirect placements, 15.0% taking exploratory actions and 58% of the task time was spent in communication events. For the TUI group, 16.2% of the total time was spent making direct placements, 12.9% making indirect placements, 42.9% taking exploratory actions and another 25% in communication.

Table 10 provides the proportions of counts for each event class relative to the total number of events. For example, this relative measure reveals that pairs in both GUI and TUI groups participated in a relatively similar number of communication events (44.0% and 41.3%).

6.2.4. *Interaction Events: relative measures for hands-on events only*

We now provide summaries of relative measures, which focus on the proportion of active manipulation time spent in each event type. This enables us to make a proportional comparison of only hands-on event classes. Table 11 provides the proportions of time spent in each manipulation event class relative to the total time spent only in manipulation events. Children in the GUI group spent 38.6% their active hands-on time taking indirect actions, compared to 29.9% in the PUI group and only 15.8% in the TUI group. Children in the GUI group spent 42.2% their time taking exploratory actions, compared to 40.9% in the PUI group and a much higher 63.7% in the TUI group.

Table 12 provides proportions of the counts of each manipulation event class relative to the total count of manipulation events. Combining time and count results, we see that children in the TUI group took fewer indirect actions, resulting in a shorter time.

Table 7. Absolute mean event class count.

	Direct	Indirect	Exploratory	Communication	Off task
GUI	19.9	20.4	28.4	57.1	6.3
PUI	33.3	18.8	41.5	52.3	1.5
TUI	32.5	14.6	61.5	74.6	1.1

Table 8. Average number of times a piece is handled.

GUI	1.3x
PUI	1.7x
TUI	2.0x

Table 9. Proportional event class durations (of total completion time).

	Direct (%)	Indirect (%)	Exploratory (%)	Communication (%)	Off task (%)
GUI	7.3	15.1	15.0	58.0	4.5
PUI	23.8	25.1	32.8	17.1	1.1
TUI	16.2	12.9	42.9	25.9	2.1

Table 10. Proportional event class counts (of total event counts).

	Direct (%)	Indirect (%)	Exploratory (%)	Communication (%)	Off task (%)
GUI	15.3	16.7	21.6	44.0	5.2
PUI	22.6	12.9	27.6	35.9	1.0
TUI	18.4	8.6	33.4	41.3	0.6

Table 11. Proportional event class durations (of manipulation time only).

	Direct (%)	Indirect (%)	Exploratory (%)
GUI	19.3	38.6	42.2
PUI	29.2	29.9	40.9
TUI	20.4	15.8	63.7

Table 12. Proportional event class counts (of manipulation counts only).

	Direct (%)	Indirect (%)	Exploratory (%)
GUI	29.0	29.7	41.4
PUI	35.6	20.1	44.4
TUI	29.9	13.5	56.6

6.3. *Temporal analysis results*

Table 13 presents the results of LSA for the GUI group. Each table cell indicates the number of times the column event class followed the row event class. For example, we can see that of the total number of events taken in all GUI sessions, 104 indirect placement events followed communication events and 113 communication events followed indirect placement events.

Table 14 presents the results of LSA for the PUI group. In this case, there are only four sessions so the numbers are smaller than for the GUI and TUI groups. We can see that 98 direct placements and 44 (half as many) indirect placements followed communication events.

Table 15 presents the results of LSA for the TUI group. We see that 357 exploratory actions followed communication events.

Figure 3 shows a common sequence of events during the first three to five minutes of puzzle solving for a pair of children in the GUI group. Grey represents communication events; white represents an off-task event (bottom right); yellow represents indirect placement events and green represents exploratory action events. There are no direct placement events in this segment.

Figure 4 shows a common sequence of events for the first three to five minutes of puzzle solving for a pair of children in the PUI group. Red represents direct placement events.

Figure 5 shows a typical sequence of events for the first three to five minutes for a pair of children in the TUI group. The pattern of exploratory action (green)

Figure 3. Typical GUI event sequence for first 3–5 minutes (grey = communication, yellow = indirect, green = exploratory).

Figure 4. Typical PUI event sequence for first 3–5 minutes (grey = communication, red = direct, yellow = indirect, green = exploratory).

Table 13. Lag sequential analysis (GUI).

GUI, *n*= 16	Direct placement	Indirect placement	Exploratory actions	Communication	Off task
Direct placement	8	1	7	103	3
Indirect placement	2	2	11	113	1
Exploratory actions	22	18	25	110	2
Communication	96	104	132	0	31
Off task	0	0	0	25	2

Table 14. Lag sequential analysis (PUI).

PUI, *n*=8	Direct placement	Indirect placement	Exploratory actions	Communication	Off task
Direct placement	11	8	21	124	3
Indirect placement	6	3	12	56	0
Exploratory actions	52	21	27	79	3
Communication	98	44	118	0	1
Off task	1	1	1	0	0

Table 15. Lag sequential analysis (TUI).

TUI, *n*=16	Direct placement	Indirect placement	Exploratory actions	Communication	Off task
Direct placement	15	10	43	197	1
Indirect placement	6	2	10	96	1
Exploratory actions	87	35	78	296	3
Communication	157	67	357	3	9
Off task	0	1	4	3	0

and communication (grey) events gives way to direct placements (red) as the session unfolds. There are few indirect placement events (yellow).

Figure 6 shows a typical sequence of events seen in successful pairs. This sequence is the last two minutes of puzzle completion for a pair of children in the TUI group.

Sections 6.2 and 6.3 reveal differences in absolute performance measures; absolute and relative interaction behavioural measures; and temporal sequences of events between groups. We next discuss our findings, focusing on the interrelations of measures, which reveal patterns that are not entirely evident by looking at individual measures.

7. Discussion

We begin the discussion with consideration of interface features and interaction behaviours that can be seen to implicitly support or 'make room' for thinking skills development, and then discuss explicit support for skills development that may be inferred from our findings. As pragmatists, we present our claims not as 'true' but as 'real' (i.e. observed in a specific situation) and therefore potentially useful and transferable to other designs (Nelson and Stolterman 2005).

7.1. *Active, engaged interaction?*

One of the claims made about hands-on approaches is that they promote active, engaged interaction. However, critiques of hands-on learning have suggested that hands-on activity does not always produce cognitive activity (Clements 1999). When we compare the absolute mean event counts for all three classes of manipulation events (adding first three columns in Table 7), we see that the mean for the GUI group is 68.8, for the PUI group is 93.5 and for the TUI group is 108.6. We also see that the average number of times that a piece is handled is 1.3 times per piece for the GUI group, 1.7 for the PUI group and 2.0 for the TUI group. We have evidence that the TUI promotes the most hands-on manipulation activity. To address the critique by (Clements 1999) and others we must explore the nature of this physical activity to try to make inferences about cognitive activity.

Figure 5. Typical TUI event sequence for first 3–5 minutes (grey = communication, red = direct, yellow = indirect, green = exploratory).

Figure 6. Successful pattern of TUI events for last two minutes (grey = communication, red = direct, green = exploratory).

Analysis of the absolute measures in Table 7 reveals that on average, there are 30% more direct placement actions in the PUI and TUI than in the GUI group. There also about 25% more exploratory actions in the PUI group and 50% more in the TUI than in the GUI group. So the additional manipulation activity in the PUI and TUI groups is largely a result of more direct placements and more exploratory actions. Direct placements are evidence of mental activity since they require mental visualisation of correct puzzle piece position. Many of the instances of exploration are related to problem space exploration (e.g. familiarisation, grouping edge pieces), again either requiring or contributing to mental skills development.

These inferences are supported by analysis that reveals a positive correlation between actively manipulating pieces and successful puzzle completion. This suggests that an optimal strategy does not involve the minimum number of manipulations to complete the puzzle, but rather 'extra' manipulations that serve various roles. While some of these actions serve pragmatic or epistemic functions (as discussed above), some seem to be 'just handling' of the pieces. What role might 'just handling' serve? One way to look at this is to compare handling pieces with the role that gesture serves in thinking. In a manner similar to that reported by Goldin-Meadow (2005), it is possible that simply handling pieces naturally and directly with the hands reduces cognitive load, freeing up resources, such as memory, for the puzzle task. While it is not always possible to visually identify when handling a piece serves the purpose of lightening cognitive load, it is clear that there is an advantage to handling pieces directly. This finding is in line with Fitzmaurice's study that found evidence that manipulating digital representations with a mouse requires more cognitive effort than similar actions on physical pieces (Fitzmaurice *et al.* 1995). We suggest that the some types of hands-on activity may free up cognitive resources, which then may be applied to skills development. Further investigation is required.

7.2. *Pragmatic actions and successful performance*

Pragmatic actions that result in direct or indirect placements are required for successful puzzle completion. An examination of task completion data (see Table 5) and a breakdown of absolute pragmatic placement times (see Table 6) reveals that although not all TUI pairs finished the puzzle, the total amount of time they spent on placing pieces in their correct positions (direct + indirect) is 5:40 minutes, compared to 8:19 for the PUI and 6:38 for the GUI. In contrast all four pairs in the PUI group completed the puzzle, requiring the same 54 placement actions (i.e. the number of pieces), but took almost two and a half minutes longer than the TUI group. Thus, pairs in the TUI group more efficiently placed pieces than pairs in the other two groups. This holds even though the TUI requires manual connection of cardboard pieces in 3D space compared to the relatively simple automatic snapping of two pieces in the GUI. Of course, in the GUI group, it may take longer to translate and rotate pieces prior to connection. Why then did the TUI pairs take less time to place pieces into their correct positions? We suggest that the guiding role of audio and visual feedback makes it faster to connect pieces in the TUI group, which is why the PUI time is longer.

However, we have seen that fast direct placements in the TUI group do not necessarily result in fewer manipulations or faster puzzle completion times. We suggest that digital feedback and direct 3D piece connection make the pragmatic aspects of the task easier and free up time and cognitive resources for children to do other things. Our data suggests that they spend this additional time exploring the puzzle space and communicating, both of which support skills development, as discussed in the next two sections.

7.3. The benefits of exploratory actions

We have evidence (shown in Tables 9 and 10) that TUI pairs spent relatively more time and took relatively more exploratory actions than the PUI or GUI pairs. What then were they exploring? From our observational notes (6.1), exploratory activity (1), simply handling pieces, was more apparent in the TUI and PUI groups. Although it served no observable epistemic purpose, the ease of handling physical pieces clearly facilitated exploration. Exploratory activity (2), peeking, served to confirm prior placements, act as a shared reference point for discussion between pairs (more on this below), and was likely, in part, a result of novelty for the TUI group. The other four types of exploratory activity (e.g. exploring connections, sorting, etc.) appear to be epistemic and result in task simplification. For example, making a pile of edge pieces makes it easier to later find them. Similarly, sorting through pieces increases familiarity with them, and makes it easier to find a specific piece later in the task.

What interface elements may facilitate the kind of exploratory actions that support successful puzzle completion? We suggest that providing ‘peeking’ feedback, which is not automatic but can be checked as required, supports exploration. In addition, we suggest that the ease of handling pieces, the provision for body movement around the table, and the provision of offline space for organising of pieces all work together to facilitate exploration. While the GUI interface had space to organise pieces, we suggest that doing so required more effort than simply using a trial and error strategy involving indirect placements (i.e. moving pieces until they snapped into place). We see this pattern in Figure 3. We suggest that the effort of using a mouse (an indirect input device) combined with automatic connectivity in the GUI puzzle hindered exploratory activity.

Epistemic actions are important for thinking skills development. They may be used to simplify a task that is too difficult to do purely mentally (e.g. visualisation). By offloading aspects of the task to the world, they provide a child with variable levels of support for developing skills based on the individual needs of that child. At the same time, the child learns epistemic strategies that may be transferred to other problem domains. The TUI features that enable effective epistemic exploration provide support for skills development during the task, and for future tasks.

7.4. Communication and collaboration

This class was mainly comprised of instances of verbal and gestural communication between partners. The pairs in the GUI group spent, on average, a summed total of 18:11 minutes communicating (9:05 per child, Table 6). Although in most cases, one child spent more time communicating than the other. This compares to 6:10 minutes for the TUI pairs and only 2:56 minutes for the PUI pairs. However, from Table 7 we see that the TUI pairs actually had on average 74.6 communication events, compared to 57.1 for the GUI pairs and 52.3 for the PUI pairs. Thus, the average length of a GUI communication event is about 20 seconds compared to five seconds for TUI pairs and three seconds for PUI pairs. The TUI pairs spent less overall time communicating than the GUI pairs but had more, shorter instances of communication. The PUI pairs communicated the least. The relative measures confirm this same pattern (see Tables 9 and 10). What then is the role of communication in each group?

In all groups we saw overlapping events where both children were engaged in communication at the same time (e.g. see overlapping grey events between children in Figures 3 and 5). This is often collaborative activity, where the children are talking together and one may be pointing. In the TUI group, these events tend to be frequent and very short, as shown in Figure 6. Temporal analysis revealed that this pattern was more prevalent at the end of sessions; suggesting short communications about progress and last collaborative efforts to place final pieces.

Why don't PUI pairs communicate? The single mouse requires some sort of collaboration if both partners are to participate. We suggest that peeking style feedback in the TUI provided a *referential anchor* and served as objects of negotiation in collaboration (as described in Suthers and Hundhausen 2003). One child peeks, which attracts the gaze of the other, and visible feedback serves to support communication about the result. LSA results confirm this pattern in the TUI group as highlighted in Table 15. The PUI interface neither required input device sharing nor provided a salient referential anchor, leading to less communication in the PUI group. While communication may only serve task completion purposes, it extremely like that it serves to support children's thinking skills development through social interaction.

7.5. *Successful puzzle completion strategies*

The puzzles were successfully completed by some pairs in all groups. By comparing successful performance measures with interaction-based behavioural measures, we can infer what constitutes a successful completion strategy. Analysis of the temporal sequences of events in *successful* pairs reveals a shared pattern (an example of which is shown in Figure 6). A common pattern associated with successful puzzle completion involved interleaved sequences of communication, exploration and direct placements. We can confirm the correlation of this pattern with successful task completion by looking at the results of the LSA. For example, we see that there are many sequences of exploratory action followed by direct placement in the successful PUI and TUI groups (see Tables 14 and 15).

We can also look at the progress throughout a successful session. In the PUI and TUI groups, a successful strategy often follows a progression from exploratory actions and both kinds of placements early in the session (see Figures 4 and 5) to exploratory actions followed by direct placements interspersed with communication events (see Figure 6) later in the session. Visualisations also revealed that most events near the end of successful sessions are short and frequent.

We can infer that in the PUI and TUI groups, the extra time taken in exploration clearly pays off and helps each child shift from an indirect strategy to a direct strategy, with placements in the TUI group taking less and less time as the session proceeds. We suggest that the combination of hands-on interaction with digital feedback in the TUI group supports a cognitive strategy that begins by leveraging physical action to support cognition and over time supports a child to more effectively utilise mental visualisations and reasoning skills to determine correct placements. From a cognitive perspective, we can infer that children may have developed mental images of the puzzle. From a more embodied perspective on cognition, we can infer that children used physical action to jump start mental skills. Both accounts explain how the specifics of a tangible style interface supported a successful strategy that enhanced children's ability to mentally solve the puzzle as the session unfolded, providing an indication of either practicing and/or improving visual search and/or visualisation skills.

Analysis of one of the successful GUI sessions showed that one child handled the mouse for the entire session and the other child contributed through communication but never handled the mouse. The mouse-controlling partner enacted a sequence of events that was very similar to the successful PUI and TUI patterns of exploration and direct placement. This suggests that a factor contributing to the common GUI pattern of indirect and communication events may be the need to have two children switch control back and forth between them. If this observation holds, then switching may inhibit the development of a successful exploratory and direct placement strategy. This requires further investigation.

8. Recommendations for design

We generalise our findings and make recommendations for interaction design for children for mental skills development related to spatial problem solving.

(1) Input designs that enable manipulating objects naturally and directly may reduce cognitive load, freeing up resources, such as memory, for skills development. For a task requiring object selection, a mouse may be the best input device. However, object rotation and translation may be better supported by direct input methods (e.g. TUI, multi-touch). Hybrid methods should be explored.

(2) Input and display designs that enable ease of object manipulation and provide flexible space in which to do so, support children to explore the problem space.

(3) Providing objects that can be shared (either physically or visually) supports communication between children. However, that communication may be about sharing rather than about the task unless the shared object is explicitly

linked to the task, which then supports communication about the object in the context of the task.

(4) Input designs and tasks that enable variable degrees of offloading of mental operations to physical actions (i.e. epistemic actions) may support both immediate task completion and longer term skill development.

(5) Feedback that guides children to complete pragmatic elements of the task (e.g. supports 'checking') but does not complete task for them (e.g. snap in place) may both free up resources and time for skills development and support an evolving approach to task completion rather than static trial and error approach, which may also support task completion but not skills development.

Clearly no one interaction style fits all. The specifics of the design context will determine the best approach. However, tangible interaction provides unique opportunities to support the development of thinking skills in areas where physical interaction is beneficial and can be augmented with digital feedback that facilitates social interaction and skills development.

9. Conclusions

We present an exploratory study that investigates the benefits of different hands-on interaction styles for a spatial problem solving task (jigsaw puzzle). Our contributions include both a video analysis methodology and empirical findings. Our video analysis approach supports quantitative analysis of children's performance and interaction-based behaviours, and allows us to compare across different styles. Our empirical findings indicated that the combination of direct hands-on input style with audio-visual feedback facilitated by the TUI supported a successful style of interaction with a slight time cost for the puzzle task.

We inferred that this approach enhanced children's ability to mentally solve the puzzle as the session proceeded. The GUI rarely supported a successful strategy but when it did, the strategy was a variant of that seen in the tangible group. We suggest having a single mouse shared with a pair of children inhibited the development of a successful mental strategy. The physical cardboard puzzle group showed less communication and less exploration but pairs frequently completed the puzzle. We concluded that effective TUI design can result in pragmatic, exploratory, collaborative and cognitive benefits.

This is the first known study to explore the mechanisms underlying the potential benefits of children's hands-on interaction with tangibles for spatial problem solving tasks. Future work is needed to apply this methodology to other problem solving tasks that involve object manipulation, to both validate the methodology and to determine if findings can be generalised to other classes of tangibles. We hope that the findings here provide some guidance for designers wondering when a TUI is beneficial and when a mouse will do.

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