Hands on What? Comparing Children's Mouse-based and Tangible-based Interaction

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ABSTRACT
We investigate the similarities and differences – in terms of quantitative performance and qualitative behaviors – between how children solve an object manipulation task using mouse-based input versus tangible-based input. This work examines the assumption common in tangible computing that direct physical manipulation is beneficial for certain spatial tasks. We describe an ecologically valid comparison of mouse-based versus tangible-based input for a jigsaw puzzle task in order to better understand the tradeoffs in choosing input and interaction styles. We include a traditional cardboard puzzle for comparative purposes. The results of an experiment with 132 children indicate children are more successful and faster at solving puzzles using a tangible-based approach. Detailed temporal analysis indicates that pairs in the tangible group spend most of their time using a combination of epistemic and pragmatic actions which support mental problem solving. Conversely, pairs in the mouse group use an ineffective trial and error strategy.

Categories and Subject Descriptors
H5.2.[Information interfaces and presentation]: User Interfaces – *Evaluation/methodology*; *Interaction styles; Input Devices and strategies.*

General Terms
Measurement, Experimentation, Human Factors, Design.

Keywords
Input methods, interaction styles, video analysis, embodied interaction, tangible computing, tangible interaction, object manipulation, digital tabletop, children, jigsaw puzzle, evaluation, methodology, comparative experiment.

1. INTRODUCTION
The rise of tangible and surface computing has resulted in the development of many new applications which rely on direct manipulation of physical objects as input to digital systems (e.g., [3, 7, 16]). Underlying these applications is the assumption which suggests that supporting users' continuous physical actions on digital objects is beneficial (e.g., [19, 22, 26]). A common argument is that interacting with certain classes of applications through tangible interaction is more "natural" than using mouse-based interaction. Naturalness is subject to interpretation and is difficult to measure objectively [4]. However, it is assumed that the physical affordances of tangible interaction will result in improved efficiency and effectiveness. Other common assumptions are that tangible interaction in spatial tasks may make the problem easier to solve and may promote users to find new solutions in the problem space. For example, a range of tangible work benches were created designed to leverage natural physical interaction with spatially distributed objects (e.g., [23, 24]).

For children, proponents of hands-on learning have turned their attention to tangible user interfaces (TUIs) for similar reasons and have made even stronger, but largely unexplored, claims (e.g.,[6, 18, 28]). To date, these assumptions of benefit remain controversial. Recent studies investigating the similarities and differences between indirect (mouse) and direct (touch) input to desktop computational systems have revealed that mouse-based interaction is, for some tasks, faster and more accurate than touch-based approaches [4]. The authors suggest that the full benefit of direct input may require larger horizontal surfaces and spatially structured tasks to become evident. In addition, comparative studies to date have been confined to investigations of direct input in the form of touch rather than direct input through tangible objects. Comparative studies of indirect and direct input methods involving tangible objects remain to be investigated. With their more limited dexterity, children are an ideal group to start to test these assumptions with.

In this study, we investigate, in detail, the similarities and difference in interactional patterns that arise when children use different input approaches to solve the same task. Our goal is to better understand the benefits of tangible interaction and to work towards generating guidelines that suggest when tangible interaction may be beneficial and when mouse-based interaction will be sufficient. We focus on a spatial task problem solving which involves manipulation of objects. We provide an overview of our mixed method approach for comparing traditional, mouse-based and tangible interaction. We report on our experiment with 132 children conceived to explore if tangible input is faster, easier and promotes more exploration when solving a jigsaw puzzle task.

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2. BACKGROUND

This section provides a description of the role of physical manipulation in children's learning and provides an overview of open questions in the study of input methods for object manipulation tasks.

2.1 Children and Hands-on Activities

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 learning and thinking [11]. For example, Goldin-Meadows suggests that a discrepancy between children's verbal and gestural explanations can indicate a readiness for learning and that students who emulate teacher's gestures in problem solving may learn faster [5]. Other studies suggest that various cognitive operations (e.g., spatial memory, lexical retrieval) are degraded when the use of hands is prevented [15].

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 [17]. Historically, Friedrich Froebel [1] and Maria Montessori [14] are credited with popularizing a hands-on approach to learning that involves the manipulation of physical materials. Manipulatives are educational materials which are designed so some aspect of their physical form represents abstract concepts. Although not uncontroversial, the use of physical manipulatives has been shown to support young children's understanding of mathematical concepts [25].

Recently, the manipulative approach has been extended to computational domains [e.g., [12, 13, 18]. Proponents of this approach claim that the role of hands-on action on physical computational objects can make abstract concepts more accessible to children [20]. Less widely appreciated is the value of actions that can simplify mental tasks which do not involve abstract concepts or symbolic representations [9]. For children, there is a benefit to supporting physical actions on computational objects which can make difficult mental tasks easier to perform. For example, we propose that the physical manipulation of jigsaw puzzle pieces makes the requisite tasks of visual search, image visualization and spatial rotation easier to perform. Task completion requires the tight coupling of mental and physical operations.

2.2 Indirect versus Direct Object Manipulation

While there has been considerable research comparing various aspects of input devices with adults [4], there has not been a study that compares indirect mouse input with direct tangible object input. And while many comparative studies have suggested guidelines for choosing the appropriate input devices, most of these studies have dealt with adults and with content input or command execution involving single pointing tasks. No research has investigated the benefits of different input approaches for children's physical object manipulation tasks. There are many open questions which concern the interrelation between input method and interaction for a task that requires manipulation of objects or pieces (e.g., spatial planning, tessellation, spatial puzzles). For example, what are the main differences between how physical objects are manipulated with the hands compared to how digital representations of those objects are manipulated with a mouse? Does indirect single (mouse) or direct bimanual (tangible) manipulation take longer? If users take longer with one method, does this mean it is more difficult to use for that task? Does indirect (mouse) or direct (tangible) interaction with objects better support users to offload difficult cognitive operations (e.g., mental rotation) to physical interactions and thus make tasks easier to complete? Does indirect (mouse) or direct (tangible) interaction better support users to explore the problem space?

3. METHODOLOGY

In order to explore the similarities and differences between mouse-based and tangible input styles and resulting interaction, we designed a semi-experimental comparison of school-aged children solving jigsaw puzzles using three input methods and associated interface styles: traditional cardboard puzzle, mouse-based graphical user interface (GUI) puzzle and tangible user interface (TUI) tabletop puzzle.

The traditional cardboard puzzle is included for comparative purposes. For example, it allows us to determine whether tangible interaction is slower than interaction with a non-augmented, traditional puzzle. The single mouse configuration is by far the most frequent found in children's classrooms, community centres, libraries and homes. Tangibles, while confined mainly to research labs, are typically placed on a horizontal surface. For reasons of ecological validity we used a single mouse graphical user interface (GUI) approach and a tabletop for the tangible user interface (TUI) condition. In this way other factors (e.g., number of access points, number of active users, display size, display orientation) which are intertwined with interaction style in everyday settings are taken into account, resulting in a holistic picture of interaction in each case.

3.1 The Roles of Manipulation in a Jigsaw Puzzle Task

A jigsaw puzzle is a visual search activity that is traditionally solved by two or more players using a combination of single and two handed manipulation of physical objects. Solving a jigsaw puzzle requires a combination of purely internal mental operations with physical operations on objects [2]. Physical manipulation may serve three intertwined roles in jigsaw puzzle solving. First, players may manipulate pieces simply to move pieces into their correct positions. We call these *direct placement actions*. Second, players may manipulate pieces on route to their correct placement because doing so makes mental operations of visual search, image visualization and/or spatial rotation easier to perform by offloading part of each operation to physical action in the environment [9]. We call these *indirect placement actions*. Third, players typically explore the problem space (e.g., organize puzzle pieces into groups containing corner pieces, edge pieces, or pieces of the same color or shape). These actions result in a simplification of the task through changing the environment. Their function is epistemic [10]. We call these *exploratory actions*.

3.2 Hypotheses

Most comparative studies of input styles rely on measures of task time and accuracy, supplemented by user preference measures. However, it is misleading to assume that speed and accuracy are the only factors to consider in interaction. This is particularly true with children where making a task easier sometimes reduces the learning taking place [21]. Our research design was driven by our research questions and the claimed "naturalness" benefits of tangible interaction. It may seem obvious that the tangible approach will be faster since the interaction technique supports multi-access and bimanual interaction (see H1 below for hypothesis one). However, looking at speed alone ignores other potential benefits and limitations of each approach. Accuracy is less relevant for a jigsaw puzzle task since the visual and physical forms constrain possible connections to correct ones. We suggest that an approach might be beneficial if it is easier. In a pilot study, a puzzle was implemented in a GUI with a smaller screen. Few pairs completed the puzzle, and many stated that it was too difficult. From this we propose if the task is easier (and sufficiently engaging), it is likely that more pairs will successfully complete it (H2). One way it may be easier is if it promotes offloading of difficult mental tasks to easier physical ones [8]. An input method would make the task easier by facilitating the user to take more actions in general (H3), and specifically more indirect than direct actions (H4). Recall that direct action serves only to place pieces in positions which have been mentally derived. An approach might also be beneficial if it supports more exploration of the problem space. For example, it promotes exploratory actions (H5).

In this paper we look for evidence to support five specific hypotheses:
H1: Pairs will complete the puzzle faster the first time using tangible input compared to using mouse input.

H2: More pairs will complete the puzzle at least once using tangible input compared to using mouse input.

H3: Pairs will spend relatively more of their first puzzle completion time taking some form of action on puzzle objects using tangible input compared to using mouse input.

H4: Pairs will spend relatively more of their first puzzle completion time making indirect placement actions rather than direct placement actions when using tangible input compared to using mouse input.

H5: Pairs will spend relatively more of their first puzzle completion time making exploratory actions when using tangible input compared to using mouse input.

3.3 Design of the Study

In order to facilitate a comparative experimental approach, a traditional cardboard jigsaw puzzle was used as well as the same jigsaw puzzle implemented on a mouse-based GUI system and a tangible tabletop system (as described in [27]). The independent variable was input style (traditional, mouse, tangible). There are other factors that vary with input style in common computer configurations. Key differences between the traditional, graphical and tangible puzzle implementations are shown in Table 1. We discuss possible effects of these factors in the Results and Discussion section. We used a between subjects design to avoid order effects seen in the pilot studies (e.g., novelty preference if tabletop was used first). Pairs of children were given the opportunity to play with the puzzle using only one input method. We used a collaborative, paired condition since jigsaw puzzles are commonly done by pairs of children.

3.4 Participants & Procedure

We recruited 132 children aged 7 to 10 years old (69 boys and 63 girls) from the regular visitor population of a local science centre over a four week period. Ninety percent 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. The laboratory was physically, visually and acoustically separated from the main exhibit spaces to limit distractions. The duration of each session for a pair was 30 minutes. 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 (i.e., a viable alternative activity). After 15 minutes, the children were asked to stop. They completed a post-questionnaire and closing interview as described in [27]. All sessions were videotaped.

Table 1. Differences in implementation features.

	Trad	GUI	TUI
Direct object manip.	+	–	+
Multi-user, bimanual	+	–	+
Horizontal Display	+	–	+
AV feedback	–	+	+
Tactile feedback	+	–	+
Integration of I/O space	+	–	+

3.5 Measures

This study design facilitated the collection of quantitative time and completion data and qualitative video data which was coded and quantized. We recorded total session time; time for first play; time for second play; number of starts; and number of completions for 66 sessions (22 traditional, 21 mouse, 23 tangible). Analysis and interpretation of these five variables are reported in [27]. Few participants finished the puzzle more than once. Therefore in this paper we focus on detailed analysis of the first attempt at puzzle completion (CT_1). Twenty-four random sessions (8 traditional, 8 mouse, 8 tangible) were analyzed using video time stamps to determine the end condition (complete, quit, ran out of time). Subsequent video analysis of 20 sessions selected for minimal occlusion (4 traditional, 8 mouse, 8 tangible), focused on the first puzzle play segment of the session. Each session was coded twice, once for each participant (40 participants). 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.

Subject sessions were coded using an event based 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. Based on the roles of object manipulation in jigsaw puzzle solving, we used three classes of touch events: direct placement, indirect placement and exploratory. A *direct placement* touch event (DP) is when manipulation (e.g., translocation or rotation) only serves to orient the piece to the correct location (figures 1, 2). We can visually identity direct placement event when a child

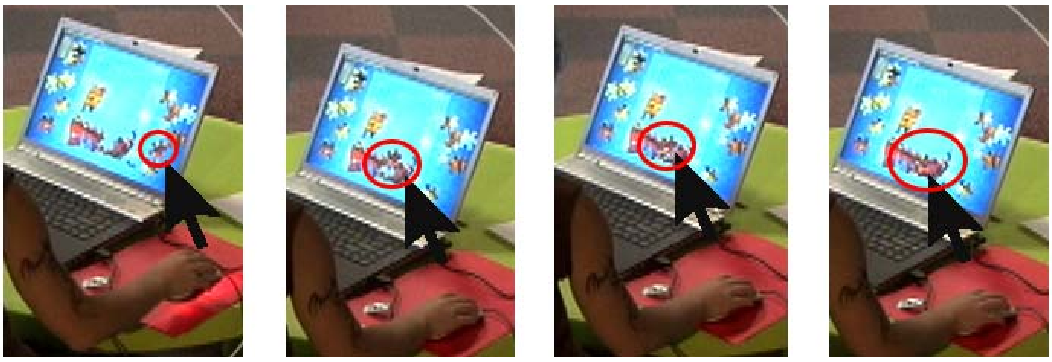

Figure 1. Direct placement using a mouse as input to a graphical user interface.

Figure 2. Direct placement of a tangible object on a digital tabletop.

Figure 3. Indirect placement of a tangible object on a digital tabletop.

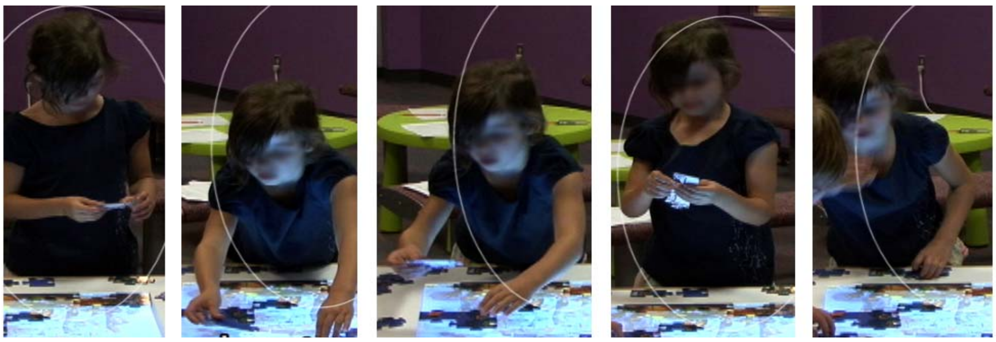

Figure 4. Exploratory action using tangible objects on a digital tabletop.

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 (IP) occurs when the participant manipulates the piece in order to determine where it fits and then places it (figure 3). In this case, physical manipulation serves to offload some portion of mental operation to physical action. A prototypical example is when a participant picks up 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. An *exploratory* touch event (Ex) is when a participant touches or moves a piece but does not place the piece in its correct placement (figure 4). A prototypical example is when a participant organizes edge pieces by placing them in a pile. We also coded *on-task but non-touch* events (ONT) (e.g., verbal or gestural communication related to the task) and *off-task* events (OffT). Video examples of each action event class can be found at (removed for blind review).

In order to compare performance between a single mouse condition (single point access) and conditions where users can interact with any number of objects (multi-point access) we developed relative measures. Manipulation time (MT) is the absolute amount of time that each participant spends "touching" a puzzle piece, using either their hands or the mouse. MT includes direct, indirect and exploratory touches. CT is the time pairs take when they attempt to complete the puzzle from start to finish (i.e., play time). For an activity that can be done multiple times, CT_n is the nth completion time. An iteration of completion time starts with the puzzle reset (all pieces taken apart and off display) and may be completed by any one of: finishing the puzzle, quitting or running out of time. The value of MT for a session exceeds completion time (CT) since the MTs for each participant in a pair is summed. From this we can derive relative manipulation time for a pair of participants for their first puzzle completion (RMT_{CT1}). In general RMT is the summed MTs for each participant in a session divided by n times the CT_1 (where n = number of participants). For a pair of participants we have,

$$RMT_{CT1} = \frac{[MT_{CT1} \text{ subject a} + MT_{CT1} \text{ subject b}]}{[2^*CT_1]}$$

RMT_{CT1} gives a relative proportion of the puzzle first completion time that participants spent manipulating puzzle pieces. For example, RMT_{CT1}= .75 means that 75% of the time taken to complete the puzzle the first time was spent with one or both participants manipulating puzzle pieces. We can also calculate relative measures for other event classes. For example, $ROTNT_{CT1}$ is the relative time during first completion spent in on-task but in non-touch activity (OTNT). Similarly, $ROffT_{CT1}$ is the relative time spent during first completion time in off task activity (OffT).

In order to further examine the proportion of touch activity spent in direct, indirect and exploratory actions we develop a second relative mean time metric. We can calculate RMT for each kind of touch event as a percentage of active manipulation time only. We then have relative measures of direct placement (RMT_1.DP), indirect placement (RMT_1.IP), exploratory (RMT_1.Ex). These variables give us an indication of the breakdown of manipulation time (MT) into direct placement, indirect placement and exploratory actions only for active manipulation time. For a pair of participants we have,

$$RMT1.XX = \frac{[MT1.XX \text{ subj a} + MT1.XX \text{ subj b}]}{[2^*MT1]}$$

For example, RMT1.DP = 0.15 means that 15% of the time actively manipulating objects was spent with one or both participants taking direct placement actions on puzzle pieces.

4. RESULTS AND DISCUSSION

The majority of results reported here are based on detailed coding of video of participants solving the puzzle for the first time using Noldus Observer XT and subsequent statistical analysis of event duration and frequency using SPSS.

4.1 Quantitative Results

4.1.1 H1: Time to First Completion

Analysis based on the 66 pairs of participants revealed that on average, time to first completion was longest for the mouse condition (13:12 minutes), one minute less for the tangible condition (11:31) and another minute less for the traditional condition (10:32) (table 2). ANOVA results for first completion time showed a statistically significant main effect at the p<0.005 level (F(2,63)=5.787, p=0.005). Independent samples t-tests between pairs revealed that the average time spent on first puzzle completion was significantly longer for the mouse condition than that for the tangible condition at the p<0.05 level (t=2.126, p=0.04) and than the traditional condition at the p<0.001 level (t=3.767, p=0.001). However, no significant difference was found between the tangible and the traditional conditions. We have evidence to support hypothesis one (H1). It took participants longer to solve the puzzle using the mouse puzzle implementation than with either the traditional or tangible implementations. It is important to check this starting assumption. It is also worth noting that pairs using the tangible and traditional puzzles did not complete the puzzle twice as fast, which you might expect since both users could be physically active at the same time.

Table 2. Time to 1st completion (minutes) (n=22, 21, 23).

CT_1	Min	Max	Mean	StdDev
Trad	6:43	15:00	10:32	2:25
Mouse	6:53	15:00	13:12	2:12
Tangible	5:44	15:00	11:31	3:02

4.1.2 H2: Successful Completion

Analysis of frequency count for all 66 sessions of the number of successful first completions indicated that 91% of the traditional pairs; 74% of the tangible pairs and 52% of the mouse pairs completed the puzzle once. Results of the Kruskal-Wallis tests indicated that the number of successful completions was significantly different across the three conditions at the p<0.005 level (χ^2(2)=11.67; p=0.003). Mann-Whitney tests results revealed that number of successful completions was significantly higher for the traditional than mouse condition at the p<0.005 level (U=126.0, p=0.001). The number of completions was also significantly higher for the tangible condition than the mouse condition at the p<0.05 level (U=157.5, p=0.019). However, no significant difference in the number of successful completions was found between traditional and tangible conditions. We have evidence to support hypothesis two (H2). More pairs completed the puzzle using tangible input than using the mouse input.

Video analysis of end conditions based on 24 sessions revealed that all eight pairs using the traditional puzzle completed it (table 3). Six pairs of the eight pairs using tangible input completed the puzzle in less than 15 minutes; and two pairs ran out of time. Three pairs using mouse input completed the puzzle; two pairs quit; and three pairs ran out of time. Based on this subsample and analysis of session observational notes, we begin to see a pattern where pairs using the mouse more frequently quit and ran out of time than in the other conditions. Pairs using tangible input rarely quit but occasionally ran out of time. Pairs using the traditional puzzle neither ran out of time nor quit. Overall, we suggest that the mouse input method took longer to use (time data) and was more difficult and/or frustrating to use (interview feedback). Pairs using tangible input took longer to solve the puzzle than those using the traditional puzzle but neither group found either implementation difficult or frustrating to use. The extra time spent on the tangible puzzle was largely due to the time spent exploring and using audio visual feedback. However the results should be interpreted with caution since only 24 sessions were analyzed in detail.

Table 3. Frequency of completion codes (n=8 for each).

	Complete	Quit	Out of Time
Trad	8	0	0
Mouse	3	2	3
Tangible	6	0	2

4.1.3 H3: Time Spent Manipulating Pieces

In order to compare the mean times participants spent manipulating puzzle pieces during the first play of the puzzle (CT_1) we look at both absolute and relative measures. Table 4 shows the absolute mean time a single participant spent actively manipulating pieces during the first puzzle play. The results show that participants in the mouse condition spent on average about four and a half minutes of the average thirteen minutes actively manipulating pieces (i.e., a single subject was on average active 35% of the time). A single participant in the tangible condition spent, on average, about eight of the eleven and a half minutes actively manipulating pieces (i.e., a single subject was on average active 71% of the time).

However, since we have single user and multi-user conditions and significantly different first play times (CT_1), a relative comparison is more meaningful. Table 5 shows the relative proportion of first play time spent with either or both participants actively manipulating pieces versus engaged in on-task but non-touch or off-task behaviors. Relative manipulation times (RMT) were much higher for the traditional and tangible conditions than for the mouse condition. We did not use inferential statistics to compare RMTs since the number of participants was low. However, we have evidence to support hypothesis three (H3) that pairs spent relatively more of their first puzzle completion time taking some form of action on puzzle objects using the tangible input approach compared to using mouse input. Participants handled pieces for approximately twice of much of their play time in the traditional and tangible conditions than the mouse condition. This corresponds to the fact that only one participant in a mouse group pair could handle the mouse at a time. However, while average first play time for all groups was within the range 10:32 to 13:12 minutes, the pairs in the mouse condition who managed to complete the puzzle did so using almost half the amount of active manipulation time. Conversely, pairs in the traditional and tangible conditions were almost twice as active in manipulating puzzle pieces.

Table 4. Absolute mean manipulation time per participant for first puzzle play (minutes) (n=4,8,8)

MT_{CT1}	Min	Max	Mean	StdDev
Trad	5:46	9:33	7:02	2:34
Mouse	2:47	5:56	4:40	3:27
Tangible	4:33	13:37	8:08	4:11

We can see in Table 5 that pairs in the mouse condition spent more than twice the time on task but not touching the mouse (**$RONT_{CT1}$**). We also notice that in the traditional and tangible conditions, children still participated through gesture and voice even though they were not required to do so by the physical constraints of the task. For example, children in the tangible condition spent on average, 25% of their session on task typically communicating with their partner and not manipulating puzzle pieces.

Table 5. Relative proportions of manipulation time (MT), on-task but non-touch (ONT) and off-task (OffT) in first play (n=4,8,8).

	RMT_{CT1}	$RONT_{CT1}$	$ROffT_{CT1}$	CT_1
Trad	79%	17%	4%	100%
Mouse	37%	58%	5%	100%
Tangible	72%	25%	3%	100%

Frequency of event occurrence data showed a mean of 58 on-task but non-touch **(ONT)** events for the mouse condition; 52 for the traditional condition and 75 for the tangible condition during first play time. This suggests that children in the tangible condition frequently worked on-task without touching pieces (e.g., gesturing, verbalizing) for short durations of time intermittently with segments of active task solving. Conversely, as is expected in the mouse conditions, the non-touch partner, often participated through gestural or verbally for longer continuous period of time. We also note that the relative off-task times for all conditions were low, as is common in interactive technology experimental work with children [27].

4.1.4 H4: Time Spent in Indirect vs. Direct Placement

We hypothesized that children would offload difficult cognitive tasks to physical manipulation of pieces. We suggested cognitive offloading would be evident by more time spent indirectly placing pieces than directly placing them in the tangible condition. This was not the pattern we found when we analyzed the video segments of first plays. Table 6 shows that relatively the same time was spent performing indirect placements in the mouse

(15%) and tangible (13%) conditions. In addition, relatively more time was spent performing direct placements in the traditional (23%) and tangible (17%) conditions than the mouse condition (7%). Table 7 shows a similar pattern. Of the time spent manipulating pieces, more time was spent directly placing pieces in the traditional (29%) followed by the tangible (23%) and mouse (20%) conditions. In addition, relatively more time was spent indirectly manipulating pieces in the mouse condition (39%) than the traditional (31%), followed by the tangible condition (18%).

We did not find evidence that tangible users enacted more indirect placements. Therefore we have no evidence to support hypothesis four (H4) that tangible input makes it easier to offload difficult mental actions to physical interaction via indirect placement actions. However, based on our observations we suggest alternative explanations for these results. First, the video coders noticed that participants spent more of the direct and indirect placement times fiddling with connections in the traditional condition than the tangible condition. This is consistent with the finding that pairs in the traditional condition had longer relative times than the tangible condition for both direct and indirect placements. In the tangible implementation audio and visual feedback may have facilitated piece connection. In the mouse condition, even less time was spent connecting pieces because the software snapped pieces together once placed, making it easier and faster to connect pieces. Second, the coders noticed that the vertical display in the GUI-mouse condition actually facilitated the kinds of visual comparisons expected in a trial and error approach using indirect placement actions (rather than direct actions).

Table 6. Relative manipulation times during first play.

RMT $_{CT1}$.	DP	IP	Ex	CT_1
Trad	23%	24%	32%	79%
Mouse	7%	15%	15%	37%
Tangible	17%	13%	42%	72%

Table 7. Breakdown of relative event types during manipulation time only.

RMT_1.	DP	IP	Ex	MT_1
Trad	29%	31%	40%	100%
Mouse	20%	39%	41%	100%
Tangible	23%	18%	59%	100%

4.1.5 H5. Relative Exploratory Action Times

As shown in Tables 6 and 7, relatively more exploratory actions occurred in the traditional and tangible conditions than the mouse condition. This provides support for hypothesis five (H5) that a physical style of interaction better promotes exploration of the problem space than a mouse based approach. Based on our observations, we attribute the additional time spent taking exploratory actions in the tangible condition compared to the traditional condition to the exploration of the audio and visual feedback in the digital tabletop implementation.

4.2 Temporal Analysis of Interaction Patterns

Using Noldus analysis features and our coded video, we created temporal visualizations of event sequences for each participant (see figure 5 for an example), conducted average frequency and duration analysis for events, and ran lag sequential analysis. Lag sequential analysis allowed us to calculate frequencies of transitions between pairs of events within the first play time. It provides information on how many times an event A is followed by an event B.

We noticed several patterns that can be interpreted together. First, we noticed that the incidence of indirect placements were more frequent in the early part of sessions for the traditional and tangible conditions and spread out throughout sessions for the mouse condition. We also noticed a pattern of exploratory actions followed by direct placements in the traditional and tangible conditions as shown in Figure 5. This was verified by lag sequential analysis. Lastly, we noticed that the average individual event durations were longer in the mouse condition and shortest and most frequent in the tangible condition. This was verified with mean frequency and duration analysis.

One interpretation of this result that fits with theories of hands-on learning is that the physical nature of the tangible puzzles combined with connection feedback promoted many frequent actions, most of which were exploratory (epistemic) that later led to quick direct placements of pieces. For example, a child might quickly manipulate a series of pieces to better understand their relation to the puzzle image or current state of the puzzle. This exploration was followed by directly placing one or more of those pieces. The handling of pieces throughout the session promoted the ability to mentally derive placements as the session progressed. Perhaps hands-on actions led to a better mental model of the puzzle which was utilized later in the session to reduce the amount of physical problem solving required.

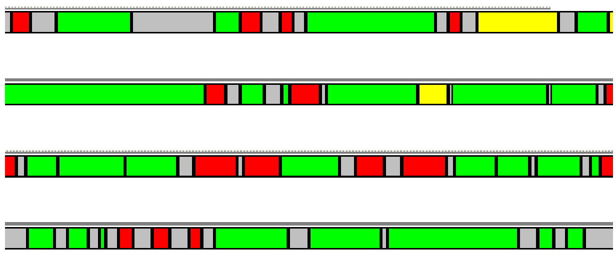

Figure 5. TUI pattern of exploratory action (green) followed by direct placement (red); on task but non-touch (grey).

We suggest that the epistemic function of exploratory actions, supported by physicality and digital feedback, made the task of finding and making correct direct placements both easier and faster in the tangible condition. This explanation is consistent with the additional time spent exploring puzzle pieces through action found in the tangible condition. In the traditional condition the average duration of indirect placement events was longer than for the tangible group. We suggest that this may be due to the lack of confirmatory feedback guiding connections. The overall effect for the traditional group was that time was equally spent making direct and indirect placements since indirect placements took longer without feedback to guide them.

Conversely, in the mouse group more relative time was spent making indirect placements. Without hands-on manipulation perhaps the puzzle remained difficult to solve mentally. Indirect placement actions indicate a trial and error strategy in which the participant repeatedly compared each piece to the digital puzzle (rather than forming a mental model) throughout the session to solve the puzzle. That is, the task never got easier and so a direct placement strategy could not be used even near the end of sessions where we expected to see more direct placements.

4.3 Limitations

There are several potential confounding factors in this experimental design including: the display orientation (horizontal versus vertical); single versus multi-access point input methods; and cardboard versus multimedia interfaces. For example, the vertical orientation of the mouse-GUI may have contributed to a visual trial and error indirect placement strategy. While this may affect the relative time spent in indirect placement, it is ecologically valid which is important to designers. Similarly the comparison of single versus multi-access point approaches may be experimentally flawed in terms of absolute measures but relative measures reveal important findings and the results are ecologically valid. The comparison of cardboard with digital multimedia is important to avoid assumptions that digital feedback is always beneficial. Lastly, none of these confounding factors invalidate the finding that tangibles supported short iterations of exploratory and direct placements which may support the development of mental strategies and ultimately led to more successful completions than a mouse-based approach. Designers must choose between supporting pairs of users on a commonly available single mouse platform and developing a tangible user interface. The compromises made in this experimental design are aimed to support designers to make informed decisions. Future research in which display factors are experimentally manipulated needs to be done to better understand how they interact with input styles and interaction types.

5. SUMMARY OF FINDINGS

We present a summary of findings that may be informative for designers choosing input styles for applications that support children's object manipulation tasks. For brevity, we refer to the traditional and tangible styles of input as direct input styles where there are no significant differences between them.

- Children completed the direct input style of puzzles faster than the mouse-GUI puzzle;
- More children successfully solved the direct input style of puzzles than the mouse-GUI puzzle;
- Children spent more time actively manipulating pieces using direct input styles;
- Children spent more time communicating (verbally and through gesture) when using the mouse-GUI;
- The vertical GUI display and mouse supported a visual trial and error approach using indirect placements;
- Children spent more time making direct placements with direct input styles;
- Children were able to more quickly connect pieces using the TUI than the traditional puzzle;
- Children spent more time enacting exploratory actions with the TUI than with the traditional or mouse-GUI;
- Children enact a temporal pattern of exploratory actions followed by direct placements using the TUI;
- Children progressed from making indirect placements early in puzzle solving to making direct placements later in the session using the TUI, suggesting the development of mental models and skills as the session proceeds;
- The mouse-GUI did not support children to progress from indirect (physical trial and error) to direct (mental) placement actions.

Overall we suggest that the combination of physicality with digital feedback and support for epistemic actions in the tangible user interface made it faster and easier for children to find and make correct puzzle piece placements.

6. CONCLUSION

This paper contributes empirically based findings from our comparative study of user's performance and behaviors using traditional hands-on, mouse-based and tangible input methods for the same spatial task. It also contributes a methodology for analyzing several kinds of hand-based actions commonly utilized in spatial object manipulation tasks. It uses relative measures to compare between single (mouse) and multi-access point (traditional, tangible) input approaches. It also relies on analysis of temporal patterns of interaction through visualizations, frequency and duration analysis, and lag sequential analysis of coded action events to clarify and better understand summative findings.

The results of our empirical study provide evidence to support the claims that hands-on direct physical manipulation of objects in a spatial problem solving task is faster, easier (in a variety of ways); supports more exploration than a mouse driven approach; and encourages short segments of on-task communication between partners. A mouse-driven approach is less successful but also supports significant gestural and verbal communication between pairs.

Our main interpretative finding is that direct handling of objects supports children to mentally solve the task through iterations of exploratory (largely epistemic) and direct placement actions. Using a mouse-driven approach children continue to solve the puzzle using a trial and error approach (indirect placement) and never fully developing a mental strategy to puzzle solving. We suggest that tangible input makes it easier to solve the puzzle, not because it is easier to offload mental tasks to indirect actions (H4) but because hands-on exploratory (epistemic) actions lead to the ability to mentally determine placements (direct placements) as puzzle solving proceeds. Tangible input supports the development of a mental model of the task through physical action. These interpretations provide support for the naturalness claim for this type of spatial task. These interpretations also highlight the need to examine not only relative time spent in various activities, but also the temporal relationships between different kinds of actions in problem solving.

The research described in this paper addresses the need for empirical studies that investigate how and why tangible interaction might be beneficial compared to mouse-based interaction. Given the attention that physical interaction is receiving in a range of ubiquitous computing domains, it is a good time to empirically explore and search for evidence of benefit of a hands-on approach.

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