Mobility Matters: identifying cognitive demands that are sensitive to orientation

G. Michael Poor[a], Guy Zimmerman[b], Dale S. Klopfer[c], Samuel D. Jaffee[c] ,
Laura Marie Leventhal[b] and Julie Barnes[b]

[a]School of Engineering and Computer Science, Baylor University, Waco, TX, 76798
[b]Dept. of Computer Science, Bowling Green State University, Bowling Green, OH, 43403
[c]Dept. of Psychology, Bowling Green State University, Bowling Green, OH, 43403

Michael_Poor@baylor.edu, gzimmer@bgsu.edu, klopfer@bgsu.edu,
jaffees@bgsu.edu, leventha@bgsu.edu, jbarnes@bgsu.edu

Abstract. Prior studies have shown benefits of interactions on mobile devices. Device mobility itself changes the nature of the user experience; interactions on mobile devices may present better support for cognition. To better understand cognitive demands related to mobility, the current study investigated presentations on a mobile device for a three-dimensional construction task. The task imposed considerable cognitive load, particularly in demands for mental rotation; individual differences in spatial ability are known to interact with these demands. This study specifically investigated mobile device orientations and participants' spatial ability. Subjects with low spatial ability were able to complete the task more effectively when shown the presentation in a favorable orientation. Individuals who saw the presentation in an unfavorable orientation and those of low spatial ability, were differentially disadvantaged. We conclude that mobility can reduce cognitive load by limiting demands for spatial processing relating to reorientation.

Keywords: Mobility, Mental Rotation, Presentation Orientation, Spatial Ability.

1 Introduction

Recently there has been an enormous expansion in the sale and use of mobile devices as information appliances. It is reasonable to ask why, or more specifically, what is it about mobile devices that make them attractive, as compared to fixed stationary devices. There are a number of obvious answers: size, convenience or price. However, if users did not find the mobile device to be at least as useful as a fixed counterpart, would these devices be so successful? It seems likely that that users experience mental workload advantages as an outcome of the very mobility of the mobile device for some tasks. For example, extracting and interpreting instructions for construction tasks[1], tasks that impose considerable mental workload in the form of mental rotation and spatial processing on users, would fit this description.

In this paper, we first review background literature, including a discussion of the likely cognitive load issues at play in construction tasks on mobile devices, specifically mental alignment of the presentation to the built object, achieved via mental rotation. We present a study that examined the role of physical device orientation on performance on a construction task. Additionally, in the study, we explored the role of an individual difference variable, spatial ability, on performance of the construction task. Finally, we present the results and we discuss the ramifications of our findings for designers.

While the constant changes in technology make the definition of *mobile device* or *mobile interaction* moving targets, for the purposes of this paper the terms *mobile device* or *mobile interaction* will imply a handheld computing device possessing a display screen and input mechanism. This definition includes cell phones, smartphones, tablets, handheld GPS (global position) systems and PDAs (personal digital assistants), but excludes traditional desktop computers with fixed displays. The key defining feature that we focus on in this paper is the ability of the user to easily reposition the display device in any desired orientation. For clarity, we will use the term *mobile device*.

2 Background Literature

2.1 Mobility Matters

It is widely believed that different interactions engage different user capabilities and draw on different elements of human cognition [cf. 12]. More specifically, researchers have noted numerous HCI issues for mobile devices [cf. 1, 4, 6, 20]. Of interest here, [31, 32] found that people used differential strategies to varying degrees of success when performing a three-dimensional construction task using instructions presented on mobile and non-mobile devices. For these tasks, the instructional presentation included interactive 3D models. Traditionally, the instructions for completing construction tasks are presented on paper, with written directions often annotating visual representations of the assembly process. Such paper based instruction presentations are notoriously difficult to use. [30] has suggested that difficulties arise in part from task demands for mental rotation. Interactive presentations offer relief from some of the limitations of the traditional paper format. In particular, interactive presentations allow the three-dimensional displayed object to be viewed from any vantage point – giving the builder a better sense of the spatial relationships of the parts of the assembly. A number of factors potentially impact performance on construction tasks, including the nature of the presentation and the spatial ability of the participants [23]. More importantly for the current study, instructions on a mobile device allow users to

---

[1] Construction tasks are ubiquitous: assembling a child's bicycle, a piece of furniture or folding a paper airplane being common examples

physically take the instructions ‘to the object’: physically orienting the instructions by holding the device proximate to a built object. Further, the richness of construction tasks would seem to make them ideally suited to highlight mental workload differences between mobile and non-mobile devices.

[31, 32] compared performance on a construction task between a mobile device presentation and a fixed upright display presentation. They found that the mobile device users were more efficient in building the target object than the fixed presentation users. [31] also found that at least 25% of the persons with the mobile device employed a strategy of moving and aligning the mobile device to the object being built during at least one building step and all but one participant removed the mobile device from its starting position during the building process. Interestingly, in [31] a number of participants with a stationary display brought the object being built to the display. In other words, in both conditions, participants aligned the physical device with the object being built. When the person could bring the presentation to the object instead of vice versa, performance was markedly improved. [31] concluded that the participants using the non-mobile presentation found the process of aligning the object to the screen was awkward, forcing them to mentally rotate in order to realign the images in the instructions to the constructed object. The participants *could* have interactively realigned the 3D presentation, in either device condition, at any point and it is possible that the subjects in [31] did this; it is notable that the mobile presentation users had better performance regardless.

2.2 Does Orientation Matter?

When a person is following computerized instructions that include visual presentations to construct an object, they have several choices as to how to align the spatial relations in the visual representation to those of the target object. They can physically move the presentation to the target via the mobility of the device, physically align the target to the presentation, manipulate the presentation of the digitally displayed 3D object, and/or perform any or all these operations mentally, without manipulating the object or the presentation. In other words, in a construction task, when the visuals in the presentation and the actual built object are misaligned, the user will mentally, physically, or interactively perform transformations to make the alignment. [30]’s results *suggest* that users are most successful when they choose to physically realign the device to the target and that they may be surprisingly unwilling to realign interactively.

As we consider the fact that in [31], mobile device subjects were able to move the device to realign the images in the presentation to the target while the fixed desktop subjects appeared to more often do this mentally, the next obvious question should be, *does it matter*? If desktop subjects are doing more mental rotations of the presentation, is there a cost? [25] claimed that internal (cognitive) representations share a second-order isomorphism to the world they represent. One outcome of this conjecture is that the greater the angular disparity between the starting orientation of an object and its rotated position, the more effort required for rotation of the object both in the real world and in their internal representations [26, 31]’s finding of performance advantages for mobile device users suggests that the mobility of the device may reduce user cognitive load by reducing need for mental rotations.

Some studies indicate that cognitive load increases as a person does more mental rotations [e.g.14, 15]. That some participants in [31] aligned the object that they were creating with the image on the fixed display whereas others aligned the mobile device with their built object highlights an obvious but critical difference between fixed vs. mobile display devices: mobile devices allow the user to change the orientation of the display, which can change the frame of reference used to specify spatial features of an object, such as identifying its top or its left or right side. In the fixed display condition in [30], participants' options for rotating the presentation to align it with an external object were: mental rotation, rotation of the real object relative to the fixed presentation and/or rotation of the interactive 3D presentation. In the mobile device condition of [31], subjects had a fourth option – they could rotate the device containing the presentation.

When an observer encounters an object in the world, two frames of reference -- and the spatial relations they define -- are important to consider. First, there is an egocentric reference frame that defines spatial relations from the observer's viewpoint (e.g., up/down, left/right). The egocentric up/down axis is typically defined by gravity, with left/right defined by what's to the left and right of the viewer's midline, respectively. Because of the invariance of gravity, the up/down axis is a primary reference frame for defining the tops and bottoms of objects and whether one object is above (or below) another [cf. 27].

There is also a reference frame intrinsic to the object itself whereby spatial relations among parts of the object are specified. Object-centered reference frames can be defined by a variety of object characteristics, such as an object's focal point [5], an axis of symmetry or elongation, or surface markings [22]. The object in Figure 1(a) has an intrinsic axis of elongation, defined by the dotted line; the triangle in Figure 1(b) has an intrinsic axis of symmetry and a focal point at its upper vertex. With both objects, the intrinsic axes are aligned with the egocentric up/down axis. If these were animate objects, people would likely construe the upper portion of each object to be its head; if they were to move they would move upwards. The triangle in Figure 1(c) is probably seen as pointing up, illustrating the primacy of the egocentric up/down axis. With its three axes of symmetry, the triangle in Figure 1(c) actually points in three directions, but the tendency to see it point up is due, in part, to the viewer using the up/down axis to assign spatial relations.

When an observer encounters an object displayed on a screen, a third frame of reference comes into play: the reference frame defined by the edges of the display. Figure 2 shows the triangle from Figure 1(c) surrounded by a rectangular frame, much as how the triangle would be seen on a desktop display. Note how the two reference frames – the egocentric up/down axis and the vertical axis of the display – are aligned, and the triangle is seen as pointing up. Due to the alignment of the viewer's and the display's reference frames, a desktop display's reference frame is redundant, providing the same spatial relations as the viewer's up/down axis.

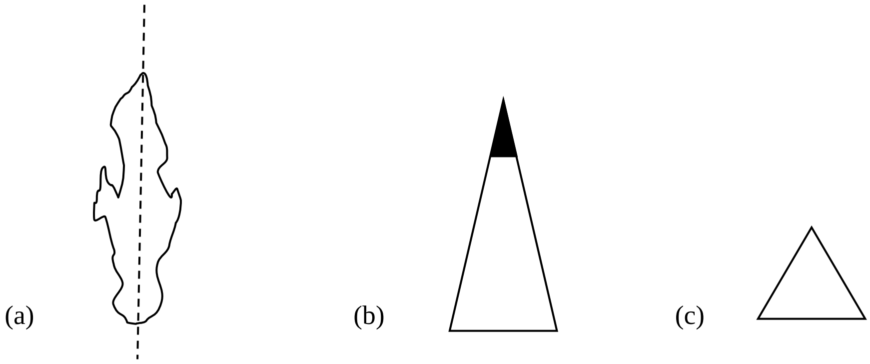

Fig. 1. (a,b,c) Objects with vertical axes of symmetry

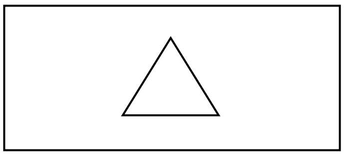

Fig. 2. Triangle object inside a display's frame of reference

With a mobile device, the reference frame defined by the display need not be aligned with the viewer's up/down axis. Figure 3 shows the triangle from Figure 2 within a rotated rectangular frame. Here, there is a strong tendency to see the triangle pointing down to the left, although it still is possible to see it pointing up. That is, by changing the display's frame of reference, the "head" of the triangle shifts from being the upper vertex to the one in the lower left. Moreover, within the context of the rotated frame, the triangle is likely seen as heading strictly to the left instead of down and to the left.

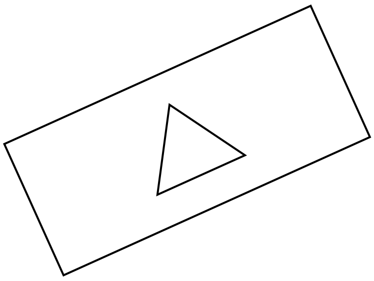

Fig. 3. Triangle inside of rotated display

As noted earlier, the mobility of mobile devices allows one to alter the display's frame of reference quite easily. Indeed, the rotated rectangular frame in Figure 3 represents just one of an infinite number of display-defined frames of reference available to the mobile device user. The interactive graphics that allow for the shape to be rotated within the display gives the user freedom to define the alignment of the presentation using whatever reference frame he or she chooses.

In the construction task in [31] there is a fourth frame of reference to consider: the one that defines the top, bottom, left, or right of the target object being constructed. In principle, there are more opportunities for the four reference frames (i.e., viewer, display, displayed object, constructed object) to be misaligned when using a mobile device than when using a fixed desktop display (i.e., viewer = display, displayed object, constructed object). Much research in cognitive psychology indicates that there is a cost in perceiving objects when viewer and object frames of reference are misaligned [cf. 13, 27]. Thus, misalignment of two frames of reference, viewer and object, can have information processing costs. To our knowledge, no research has been done that examines how users cope with the possibility of there being multiple opportunities for misalignment.

2.3 Evidence of the Importance of Presentation Orientation

Even with the possibility of physically reorienting a presentation, determining the *best* interactive realignment may in and of itself impose significant cognitive load and involve mental rotations in planning, especially for low spatial ability users. Given that many contemporary mobile devices only automatically realign in cardinal directions, should it turn out that physical orientation and spatial ability do interact on a construction task, persons of low spatial ability who cannot physically reorient to the *best* orientation will be disadvantaged unless the cognitive load for interactive realignment can be reduced.

Three older studies point to the importance of orientation in a presentation of interactive visual information. [24] found that, for map-based navigation assistance, physical rotation is the most effective form of track-up alignment on handheld mobile devices This was due to the users' difficulty to recognize a map when automatically rotated, especially when the users were not looking at the map during the time of rotation.

In addition, [28] described a comparative study of the effectiveness of four different presentations of instructions for an assembly task: printed manual, monitor-display, see-through head-mounted display, and spatially registered augmented reality (AR). Measurements were task performance (time and accuracy) and perceived mental workload. The task consisted of 56 procedural steps building an object with Duplo blocks. Participants in the spatially registered AR treatment made significantly fewer assembly errors. The authors concluded that the improvement in the AR condition was due to reduced demand for attention switching. Because the spatially registered AR appears directly on the object, it was also thought that the participants did less mental transformations between the instructions and the object.

[7] reported on a design tool to build three-dimensional, interactive and movable polyhedrons. In evaluating this tool, they found that users had a preferred orientation for the designed polyhedrons. When the figures were moved from the preferred orientation, subjects found them to be more difficult to sketch (reproduce by hand). Some participants reported elements of the preferred orientation include: 1) preference for vertical as opposed to horizontal edges (preference for either type of edges as compared to diagonal edges), 2) bilateral symmetry, and 3) stability as indicated by the polyhedron resting on a face as opposed to resting on a vertex.

2.4 The Role of Spatial Ability

Performing mental transformations, such as those described by [14] can impose a workload on working memory. In particular, the mental rotation processes can be time-consuming and error prone, particularly as the complexity of the object being rotated increases and its familiarity decreases [3, 10]. Just how much effort the mental rotation processes require also depends upon an individual's spatial ability, i.e. the ability to generate, retain, and transform well-structured mental images [16, 17]. Individual differences in spatial ability are related to individual differences in working memory function [17, 19], with transformations such as mental rotation taking longer for users with lower spatial ability, as measured by paper-and-pencil standardized spatial ability tests [8]. Mobile devices potentially provide a means for users to align a displayed object with their own egocentric up/down, limiting the need to engage in mental rotation in order to achieve alignment. The savings would be greater for those with lower spatial ability and would potentially expand the usefulness of the device to a larger population.

2.5 Summary: Background Literature

Prior research has suggested four intersecting themes: 1) Performance on a construction task is better with a mobile device than on a fixed display device 2) Construction tasks engage mental workload, much of which is involved in mental rotation to align disparate frames of reference. The cost of mentally aligning an egocentric and presented object-centric frame of reference is known to be high; the cost of realigning those frames of reference plus others from a display and a built object are not known 3) Mental rotation requires significant mental workload and 4) People differ in their abilities to perform mental rotation; those of lower spatial ability, as measured on standardized tests, find spatial tasks like mental rotation, more difficult than those of higher spatial ability. Taking these themes together, we suggest that performance on a construction task is better with a mobile device as compared to a fixed display device because the mobile device participants are able to lessen some of the mental work of aligning the presentation to the object to be built. In [20] mobile device participants accomplished the needed rotations by a combination of mental and physical rotations rather than mental rotation alone. We hypothesize that mental rotation, interactive rotation of the presentation, or rotation of the artifact is more difficult than rotating the device itself. We suggest that when rotating physically, with the immediate visual feedback as the virtual and physical object align, the participant does less mental rotation, thus reducing their mental workload.

Recognizing that people differ in their ability to do mental rotation, those of lower spatial ability, should be differentially more impaired with a stationary device – [20] did not measure the spatial ability of their participants, so we cannot be sure of this conjecture from their results relating to spatial ability.

In the current work, we start with the assumption that part of the power of a mobile device comes from the reduction in necessary work of mental rotations. We speculate that this advantage may extend further for those who are more challenged by deficits in their ability to perform mental rotations. In our study, we seek to demonstrate that having the visual presentation for a construction task aligned in a particular way, as one would be able to do with a mobile device, would lead to superior performance, than having the presentation in other orientations.

3 Study: Impact of Orientation of Presentation and Spatial Ability on Construction Task Performance

For this study our hypothesis is:

> *Orientation of a mobile device, in combination with participant spatial ability will affect performance on a construction task.*

We specifically hypothesize that at least one orientation will lead to better performance on the construction task by leading to fewer differences in frame of reference between the built object and the presentation by reducing mental rotations (and lowering cognitive/working memory load). However, because the built object itself is in a number of orientations during the presentation, we do not predict which orientation(s) would be favorable and which would impede subjects' performance on the task. Following prior work on the interaction between spatial ability and mental rotation, we also predicted that persons of low spatial ability would be differentially hampered in the less favorable orientations.

3.1 Experimental Design

We have two independent variables: Mobile Device Orientation and Spatial Ability, and two dependent performance variables, described in Section 4, relevant to the task. [20] found that time on the task was non-informative; it was not considered as a dependent variable.

3.2 **Mobile Device Orientation**.

In the study, the mobile device was physically anchored in four orientations (denoted: *left, right, top, bottom*) as shown in Figure 4a. Figure 4b shows the experimental setup with the device in the *right* orientation. The presentation of the instructions for the construction task was symmetric relative to both vertical and horizontal orientations and we collapsed the orientations into two categories: UpDown and LeftRight. While fixing the mobile device may seem counter-intuitive (removing the “mobile” aspect of the device), we have done so in order to allow for greater experimental control in order to study the effects of the frame of reference imposed by the display of the mobile device.

The participants sat upright at the table facing the instructions and were to the extent possible, in a fixed egocentric orientation; participants’ position was set so that they did not reorient the presentation by reorienting their own viewpoint.

3.3 Spatial Ability

We measured spatial ability using the Card Rotation task, a measure of two-dimensional mental rotation [8], an individual ability that should be at play, at least in part, in our construction task. Because this is not a power test (i.e., the task does not get harder at the end) the scores were calculated by subtracting the total number of wrong responses from the total number of correct responses. Our median subject score was 69. The minimum and maximum scores were -58 and 154 respectively. Using median split, participants were grouped into two categories: high and low spatial ability.

3.4 Participants

Thirty-two participants, drawn from undergraduate computer science classes, completed the task to their satisfaction with 16 persons in the UpDown condition and 16 persons in the LeftRight Condition. Two participants from each spatial ability category were dropped; they were the participants closest to the median spatial score of 69, leaving a pool of 28 participants with 14 participants in each orientation category. In terms of spatial ability, this change to the pool left 15 participants with high spatial ability and 13 with low spatial ability. Nine participants were assigned to the High spatial ability/UpDown condition, five participants to Low spatial ability/UpDown, 6 participants to High spatial ability/LeftRight and eight to Low spatial ability/LeftRight. A chi-square analysis of this frequency distribution was not significant, showing that the assignment to condition was independent from spatial ability.

3.5 Materials and Task

In previous studies we explored the effectiveness of interactive 3D graphics as a part of a system to deliver instructions for a construction task: origami paper folding [cf. 2, 30]. Paper folding does possess many representative characteristics of construction tasks: the task is non-trivial, it requires multiple manipulation steps, and it results in a 3D artifact. Researchers in multimedia learning make a distinction between single and dual presentations of instructional information [18, 21]. In single presentations, instructions are typically presented in text alone, whereas in dual presentations instructions are usually presented in text with accompanying still images or other representations [21]. A number of studies indicate that dual presentations lead to better performance [e.g. 18, 29]; this advantage has been shown with the present task [31].

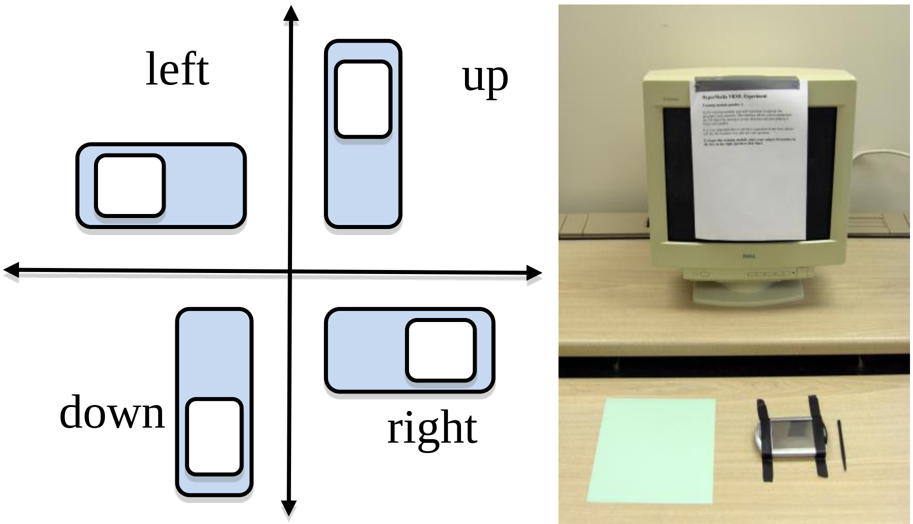

Fig. 4. a) Orientation conditions for the mobile device. b) Set up for *right* condition. Note: device is fastened to the table; paper instructions are anchored to the front of a monitor.

Our task, identical to the task used in [31], was to fold an origami whale in 25 paper folds (and unfolds), with the instructions for making the folds presented in a series of 12 steps. Approximately ½ of the steps involve 2D folds, the remainder were 3D folds, including steps to form the mouth, fins and tail. A completed whale is shown in Figure 5.

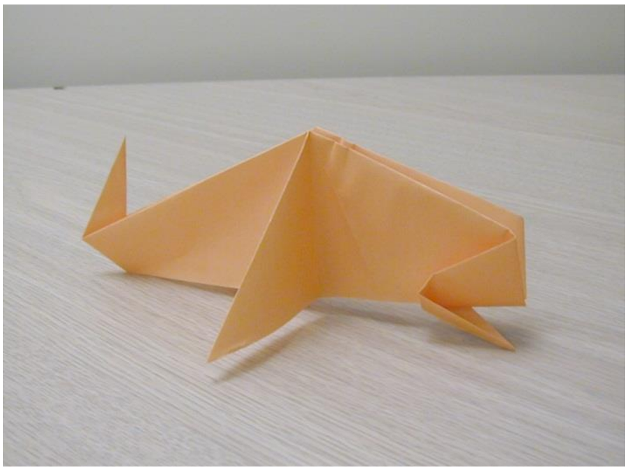

Fig. 5. The completed whale

The 3D presentation was delivered on a HP IPAQ h5455 with stylus and Microsoft Pocket PC version 3. The h5455 used the 400 MHz Intel PXA250 processor with 64 megabytes of RAM. The IPAQ and the interaction user interface were much less familiar to the participants than a smartphone or handheld GPS system; it was our thought that participants were not able to engage familiar tasks, outside of the specific experimental task, during the experiment.

The 3D interactive presentation was implemented using VRML 2.0 (Virtual Reality Modeling Language). The VRML model was rendered within Pocket Internet Explorer 5.5 using the Pocket PC Cortona VRML client plug-in. The display screen was 3.8” (diagonal) with resolution 240x320 with 16-bit color. There were two visual components to the display: the virtual sheet of origami paper (VOP/model) and the user animation/step interface. A simulated sky/horizon was also implemented to provide a spatial frame of reference for the origami paper. The user moved through the steps by clicking the forward/backward buttons on the interface. During each step the user could start/stop an animation of the desired operation (e.g., create a fold) by clicking the play/pause button. For each step that required a fold operation, the animation began by highlighting the desired fold line on the VOP; the actual fold operation was then performed on the VOP. The user also had the ability to rotate the VOP/model in any direction at any time. Technical VRML implementations details can be found in [20]. Figure 6(a) shows the 3D interactive presentation. Subjects had access to written instructions with figures printed on paper; these were anchored in front of the subject using a "flipchart" style of presentation (see Figure 6(b)).

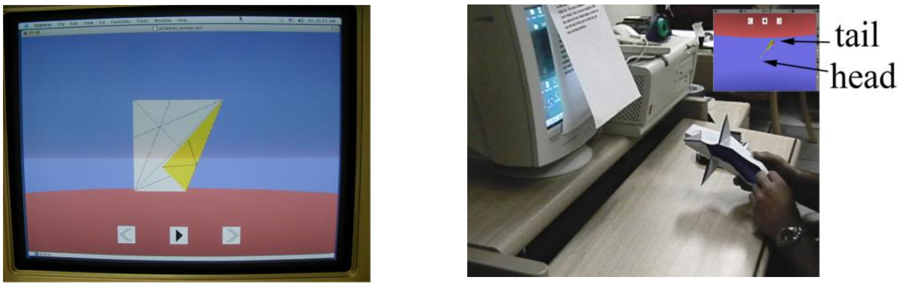

Fig. 6. a) The 3D interactive presentation b) The experimental setup; note the built whale is misaligned with the presentation (inset).

3.6 **Procedure**

The subjects completed the spatial ability test and a training task to familiarize them with the interactive controls. Then they completed the whale-folding task of twelve folding steps, used in [30, 31, 32].

3.7 **Scoring of the Folded Whales**.

Each participant’s whale was scored by evaluating every fold on the origami paper. Each fold was scored as Correct, Error and/or Recrease. If a subject performed a fold incorrectly and then folded correctly, these were scored as different folds (one correct and one error). In addition, a correct fold might be recreased. The range of Correct Folds was 0 - 25; of Error Folds and Recrease Folds was 0 – no maximum. Two people graded the constructed origami whales with an inter-rater reliability of 0.99.

3.8 **Summary: Relating the Study to the Hypothesis**

[31] posited that construction tasks in general and the one used in this study specifically impose significant mental workload as the participants must align four frames of references (themselves, the presented instructions, the display and the built object) using a combination of mental and physical rotations. In this study, physical rotation of the display and rotation of the egocentric (participant's) frame of reference were limited or fixed by the experimental setup. Realignments were possible through the interactive rotation of the presentation, physical movement of built object and mental rotation of any of the component elements. All participants were free to rotate the interactive presentation or to move the built object. Only demands for realignment by mental rotation differed by orientation. We expected to find that persons of high spatial ability would outperform those of low spatial ability across the board, simply by the fact that the cost of mental rotation is higher for individuals of low spatial ability. Our alternative orientations simulate the various positions that a mobile device could be in. If one orientation leads to better performance, especially for persons of low spatial ability, then we would have shown that physical alignment of the display to the other experimental components does reduce mental workload on our task.

4 Results

We considered the impact of the independent variables, Orientation (UpDown vs. LeftRight) and spatial ability (High vs. Low) on two dependent variables: Adjusted Number of Correct Folds (defined as Number of Correct Folds minus Number of Error Folds) and Number of Correct Recrease Folds (multiple redundant correct folds). The subjects in this study did well on the task, as indicated by our Adjusted Correct Folds measure, with an overall mean of 16.3.

As we had multiple dependent variables, we first conducted a multivariate analysis of variance (MANOVA)[2]. The dependent variables (Adjusted Number of Correct Folds, and Number of Correct Recrease Folds) were included in the MANOVA. The main effects were significant; the interaction between Orientation and Spatial Ability was not. (Wilks' Lambda = 0.714, F(2.0,,23.0) = 4.603, $p < 0.021$ for Orientation; Wilks' Lambda = 0.672, F(2.0,23.0) = 5.607, $p < 0.010$ for Spatial Ability). A two-

---

[2] We performed a MANOVA because intuitively, it would make sense that our dependent variables were intercorrelated in some way. The MANOVA identifies significant intercorrelations among dependent measures such that these measures are not incorrectly identified as significant effects of the independent variables. While we recognize that our test may be somewhat lacking in power, we feel that, in light of the experimental design, these statistical procedures are the most appropriate.

way ANOVA revealed significant main effects of Orientation and Spatial Ability on the Adjusted Number of Correct Folds [F(1,24) = 9.323, p < 0.005) and F(1,24) = 10.539, p < 0.003, respectively]. No univariate analyses of Number of Correct Recrease Folds were significant. The means of the dependent variables are shown in Table 1. From the means for Adjusted Number of Correct Folds, persons with high spatial ability or the Left-Right orientation performed significantly better than persons with low spatial ability or UpDown orientations.

Table 1. Mean Adjusted Number of Correct Folds and Correct Recrease Folds by Spatial Ability (High Spatial Ability vs. Low Spatial Ability) and Orientation (Updown vs. LeftRight) (standard deviations in parentheses)

	Adjusted Correct Folds		Number of Correct Recrease Folds	
	UpDown	LeftRight	UpDown	LeftRight
High spatial ability	18.00 (6.90) n=9	21.50 (3.27) n=6	4.33 (2.00) n=9	2.83 (0.75) n=6
Low spatial ability	7.00 (4.30) n=5	18.00 (4.30) n=8	3.60 (3.36) n=5	4.88 (2.96) n=8

Note: Maximum value for Adjusted Number of Correct Folds is 25.

In order to understand these findings in detail, we examined the two components of Adjusted Number of Correct Folds (viz., the Number of Correct Folds and the Number of Error Folds) separately as a function of Orientation and Spatial Ability. High spatial ability participants made more correct folds than those with lower spatial ability (F(1,24) = 6.349, p < 0.019), and participants in the LeftRight orientation made more correct folds than those in the UpDown orientation (F(1,24) = 4.678, p < .041). The Orientation X Spatial Ability interaction was not significant for Number of Correct Folds. The Number of Errors, on the other hand, was significantly greater in the UpDown than in the LeftRight orientation (F (1, 24) = 5.410, p < .029). There was also a main effect of Spatial Ability, with Low Spatial Ability participants making more errors than their High Spatial Ability counterparts (F(1,24) = 4.566, p < 0.043). The Orientation X Spatial Ability interaction was also significant for Number of Error Folds(F(1,24) = 4.424, p < 0.046), showing that the performance of participants with lower spatial ability was most affected by the unfavorable UpDown orientation. The means and standard deviations are listed in Table 2.

4.1 Discussion: Study Results

Our results show significant disadvantages for participants who were in the UpDown orientation or low on a measure of two-dimensional rotational spatial ability. The disadvantages were exacerbated for persons who were both in the UpDown condition and had low spatial ability for the dependent measure, Number of Error Folds. The fact that persons of high spatial ability performed better on the construction task is not surprising – we anticipated that the construction task imposed a higher cognitive cost for persons of low spatial ability. The fact that the two orientations led to differences in performance suggests that the position of a device imposes differential demands in mental work. With a real mobile device, individuals can reduce the workload by moving the device. That the LeftRight orientation was related to improved performance suggests that the critical elements of the presentation best lined up with the object being built in this orientation. Future studies could explore the specific elements of the presentation that was influenced favorably by the LeftRight orientation.

Table 2. Mean Number of Correct Folds and Number of Error Folds by Spatial Ability and Orientation (standard deviations in parentheses)

	Number of Correct Folds		Number of Error Folds	
	UpDown	LeftRight	UpDown	LeftRight
High spatial ability	21.56 (4.50) n=9	24.33 (0.82) n=6	3.11 (2.93) n=9	2.83 (2.92) n=6
Low spatial ability	15.40 (6.54) n=5	20.88 (5.89) n=8	8.4 (4.72) n=5	2.88 (2.59) n=8

Note: Maximum value for Number of Correct Folds = 25.

5 Vertical Orientation: Does it Matter?

In our study, we manipulated the orientation only in two spatial dimensions on a flat table surface. It is possible that the flat manipulation is not ideal and that the third dimension of vertical could be key as well. In a follow up pilot study we compared the Up subjects from the UpDown group to a group of participants who saw the presentation on the mobile device in a stationary vertical position. The setup is shown in Figure 7. All other aspects of the pilot study procedure were identical to our primary study, described in Sections 3 and 4.

We chose to compare the Vertical orientation to the Up orientation from the tabletop conditions in our original study, because the Vertical presentation is also in the Up orientation but rotated 90 degrees vertically from the desk surface. We had eight subjects in the Vertical orientation (3 lows and 5 high spatial ability) and we compared this group to the original eight subjects from the Up (5 lows and 3 high spatial ability). We conducted a MANOVA with dependent variables Adjusted Number of Correct, Folds and Number of Correct Recrease Folds for the two independent variables, Orientation (Vertical vs. Up) and Spatial Ability. The only significant effect, following the MANOVA was for Spatial Ability (Wilks' lambda= 0.561, F(2.0, 11.0) = 4.3, p < 0.042). Separate univariate ANOVAs showed that Spatial Ability had a significant effect on Adjusted Number of Correct Folds (F(1,12) = 9.377, p<.01) only. So the independent effect of 3D vertical orientation did not have a significant impact on performance nor did it interact significantly with spatial ability. The means for the two groups were low spatial ability participants= 13.567, high spatial ability participants = 23.3.

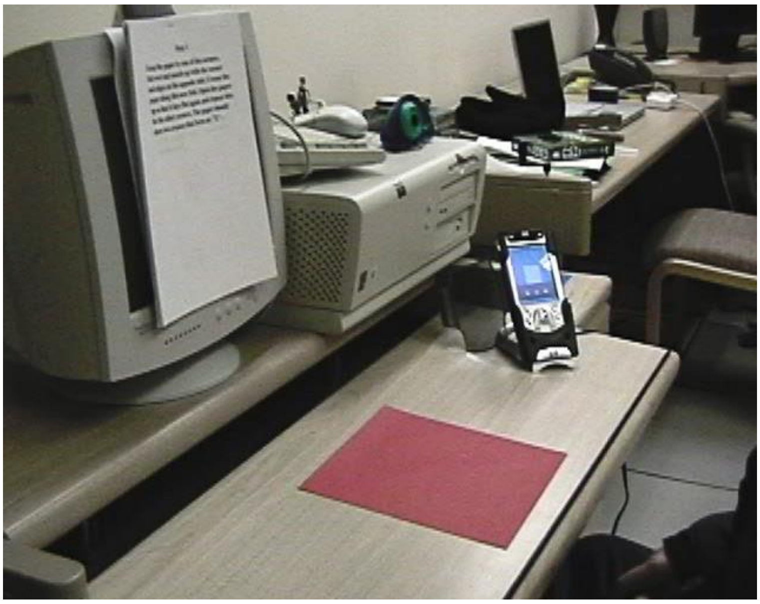

Fig. 7. Mobile device in a fixed vertical orientation.

5.1 Discussion: Pilot Study Results

For the whale folding task, the subjects were not folding the physical whale vertically; the pilot study results suggest the vertical orientation of the mobile device did not align effectively with the physical whale. The Vertical mobile device alignment also did not yield different results from the Up tabletop position. We posit that Up orientation placed the interactive presentation in a mostly vertical orientation like the position of the display in the Vertical orientation of the pilot. The LeftRight orientation, superior to the UpDown orientation, made up in part by the Up orientation, likely positioned the salient elements of the interactive presentation predominantly in the position that participants favored during whale construction and that limited demands for mental realignment.

6 Conclusions

We found that user performance was significantly affected by the physical orientation of the mobile device, spatial ability and their interaction on a paper folding task. We make our first conclusion – mobility does change the user experience at least for some tasks; enabling reorientation potentially reduces the need for mental rotations. While the study was not specifically designed to systematically control the orientations of the 3D interactive images shown, it appears that when making folds, performance was better when the model was aligned left and right. It is noteworthy that the subjects could have interactively changed the orientation of the 3D model at will. The fact that the orientation of the mobile device was a significant factor in performance suggests that the subjects did not, on at least some occasions, rotate the model to the more favorable orientation. This finding suggests that the frame of reference imposed by the display may have had greater power over the participants' mental representations of the task than the mental representation of the object itself. Prior studies have demonstrated that there is a cognitive cost for mental rotations effected to align disparate frames of reference. In order to select an interactive rotation would have required the subject to mentally rotate the model before interactively reorienting the presentation. Our results suggest that at least some of the time, subjects make tradeoffs between impaired performance and the mental effort required for mental rotations or for planning for interactive rotations. We conclude that mobility matters in part because mobility allows users to put presentations into favorable orientations and reduces the need for mental rotation.

Our results have implications for the design of presentations for mobile devices. We note that many contemporary mobile devices automatically alter the orientation of presentations on the screen, based on the physical position of the device. Should a person move a device to limit the mental work of rotating the presentation, only to have the device itself rotate the presentation, the automatic re-rotation could actually add to user workload.

Mobile devices and visual-spatial presentations of information are pervasive and likely to become more so, especially for tasks in which the mobile device can be moved to close proximity of the task [cf. 9]. Designers will be increasingly challenged to build user interfaces that do not inadvertently incorporate significant cognitive barriers to users in the form of memory load, especially for low spatial ability individuals. For individuals who are unable to physically reorient a device, our results suggest that they too may be potentially disadvantaged as they may be forced to rely initially on mental rotation to plan their interactive reorientation. Designers potentially may be able to expand the usefulness of their designs to broader spectra of the population by limiting the need for mental rotation via the mobile properties of the device.

Acknowledgements

We thank Ron Buchanan and Chris Glenn for their assistance on this project.

References

1. Abowd, G.D. & Mynatt, E.D., 2000. Charting Past, Present, and Future Research in Ubiquitous Computing. *ACM Transactions on Computer-Human Interaction*. 7 (1), pp. 29-58.
2. Barnes, J., Poor, G.M., Leventhal, L., Zimmerman, G., Klopfer, D., 2005. Look and touch: the impact of touchscreens on the delivery of instructions for inherently 3D construction tasks using web-delivered virtual reality. In: *Proceedings of IPSI-2005,* Amsterdam.
3. Bethell-Fox, C.E. & Shepard, R.N. 1988. Mental rotation: Effects of Stimulus complexity and familiarity. *Journal of Experimental Psychology: Human Perception & Performance*. 14, pp. 12-23.
4. Bouri, D., Fraser, M. Fraser, D. S. and Cater, K. 2012. Augmenting Spatial Skills with Mobile Devices. CHI 2012. May 5-10. Austin, TX, pp. 1611-1620.
5. Braine, M.D.S. 1978: On the Relation Between the Natural Logic of Reasoning and Standard Logic. *Psychological Review,* 85, pp. 1-21.
6. Dunlop, M.D. & Brewster, S.A., 2002. The challenge of mobile devices for human computer interaction. Personal and Ubiquitous Computing 6 (4), pp. 235-236.
7. Eisenberg, M., Nishioka, A., Schreiner, M.E., 1997. Helping users think in three dimensions: steps toward incorporating spatial cognition in user modeling. In: Proceedings of the 2nd International Conference on Intelligent User Interfaces IUI '97, pp. 113-120.
8. Ekstrom, R.B., French, J.W., Harman, H.H. and Deman, D., 1976. *Kit of Factor Referenced Cognitive Tests. Educational Testing Services*, Princeton, NJ.
9. Froehlich, P., Baillie, L., Simon, R., 2008. Realizing the Vision of Mobile Spatial Interaction. Interactions. January – February 2008. pp. 15-18.
10. Folk, M. D. & Luce, R. D. 1987. Effects of stimulus complexity on mental rotation rate of polygons. *Journal of Experimental Psychology: Human Perception & Performance*, 13, pp. 395-404.
11. Instone, K., Brown, E., Leventhal, L., Teasley, B., 1993. The challenge of effectively integrating graphics into Hypertext. In: *Human-Computer Interaction, Third International Conference, EWHCI '93*, pp. 290-297.
12. Jacob, R.J., Girouard, A., Hirschfield, L.M., Horn, M.S., Shaier, O., Soloway, E.T., & Zigelbaum, J. 2009. Reality-based interaction: A framework for post-WIMP interfaces. *Proceedings of ACM Conference on Human Factors in Computing Systems 2009, SIGCHI 2009*. Boston, MA. April 4-9, 2009. pp. 201-210. ACM Press. New York.
13. Jolicoeur, P. 1990. Orientation congruency effects on the identification of disoriented shapes. *Journal of Experimental Psychology: Human Perception and Performance, 16 (2),* pp. 351-364.
14. Just, M. A. & Carpenter, P. A. 1985. Cognitive coordinate systems: Accounts of mental rotation and individual differences in spatial ability. *Psychological Review,* 92, pp. 137-172
15. Klopfer, D., Athy, J., Leventhal, L. 2007. Working Memory: Just & Carpenter (1985) Revisited. *Proceedings of the 48th Annual Meeting of the Psychonomic Society.* Long Beach, California. November 15 - 19, 2007.
16. Lohman, D.F., 1988. Spatial abilities as traits, processes, and knowledge. In: Sternberg, R.J. (Ed.), *Advances in the psychology of human intelligence (Vol. 40).* Erlbaum, Hillsdale, NJ, pp.181-248.
17. Lohman, D. F. 1996. Spatial ability and G. In I. Dennis & P. Tapsfield (Eds.). *Human abilities: Their nature and assessment*, pp. 97-116. Hillsdale, NJ: Erlbaum.
18. Mayer, R.E., 2001. Multimedia Learning. Cambridge University Press, New York, NY.

19. Miyake, A., Friedman, N. P., Rettinger, D. A., Shah, P., & Hegarty, M., 2001. How are visuospatial working memory, executive functioning, and spatial abilities related? A latent-variable analysis. Journal of Experimental Psychology: General 130, pp. 621-640.
20. Mohamedally, D., Zaphiris, P., Petrie, H., 2003. Recent research in mobile computing: a review and taxonomy of HCI issues. In: *Proceedings of HCI International 2003*, pp. 9-10.
21. Paivio, A. 1986. Mental representations: A dual coding approach. Oxford University Press, New York, NY.
22. Palmer, S. E. 1999. *Vision science: Photons to phenomenology*. Cambridge, ,MA: MIT Press.
23. Poor, G. M. 2008. *The effects of varying levels of reality based interaction on a subjects' ability to perform a 3D construction task.* PhD dissertation. Tufts University.
24. Seager, W. & Stanton-Fraser, D. 2007. Comparing Physical, Automatic and Manual Map Rotation for Pedestrian Navigation. In *ACM SIGCHI Conference on Computer-Human Interaction (CHI 2007)*, ACM Press, May 2007, pp. 767 – 776.
25. Shepard, R. N. 1978. The mental image. *American Psychologist*, 33, pp. 125-137.
26. Shepard, R.N., Hurwitz, S. 1984. Upward direction, mental rotation, and the discrimination of left and right turns in maps. Cognition 18, pp. 161-193.
27. Shiffrar, M. & Shepard, R. N. 1991. Comparison of cube rotations around axes inclined relative to the environment or to the cube. *Journal of Experimental Psychology: Human Perception and Performance*, 17, pp. 44-54.
28. Tang, A., Owen, C., Biocca, F., Mou, W. 2003. Comparative effectiveness of augmented reality in object assembly. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems CHI '03, pp. 73-80.
29. Teasley, B., Leventhal, L., Instone, K., Brown, E., 1997. Effective illustrations in interactive media: what works? In: Human-Computer Interaction, INTERACT '97, pp. 197-204.
30. Zimmerman, G., Barnes, J., Leventhal, L., 2000. Delivering instructions for inherently-3D construction tasks: an evaluation of authoring environments for multimedia presentations. In: Proceedings of the 2000 International Computer Symposium, pp. 126-131.
31. Zimmerman, G. W., D. Klopfer, G.M. Poor, J. Barnes, L.M. Leventhal, S. Jaffee, 2011. How Do I Line Up?: Reducing Mental Transformations to Improve Performance. In *HCI International 2011*, 9-14 July 2011, Orlando, Florida,.
32. Zimmerman, G., Barnes, J., Leventhal, L., 2003. A comparison of the usability and effectiveness of web-based delivery of instructions for inherently-3D construction tasks on handheld and desktop computers. In: *Proceeding of the Eighth international Conference on 3D Web Technology. Web3D '0*3, pp. 49-54.