# Prospective Motor Control on Tabletops: Planning Grasp for Multitouch Interaction

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## ABSTRACT
Substantial amount of research in Psychology has studied how people manipulate objects in the physical world. This work has unveiled that people show strong signs of prospective motor planning, i.e., they choose initial grasps that avoid uncomfortable end postures and facilitate object manipulation. Interactive tabletops allow their users great flexibility in the manipulation of virtual objects but to our knowledge previous work has never examined whether prospective motor control takes place in this context. To test this, we ran three experiments. We systematically studied how users adapt their grasp when asked to translate and rotate virtual objects on a multitouch tabletop. Our results demonstrate that target position and orientation significantly affect the orientation of finger placement on the object. We analyze our results in the light of the most recent model of planning for manipulating physical objects and identify their implications for the design of tabletop interfaces.

### Author Keywords
Movement planning; acquisition and manipulation; range of motion; end-state comfort effect; multitouch; tabletops

### ACM Classification Keywords
H.5.2 [Information Interfaces and Presentation]: User Interfaces - Graphical user interfaces;

## INTRODUCTION
The manipulation of virtual objects has a central role in interaction with tabletops. For example, users move and rotate documents and pictures around the surface to share them with other users. Graphical designers manipulate information and graphical objects to create new content. Multiple users work collaboratively to create schedules, make decisions, or solve complex problems. In all these scenarios, users interact with their hands and their fingers; they grasp, translate, and rotate virtual documents as they would do with physical objects.

Literature in experimental Psychology contains a large body of work that studies the manipulation of physical objects. In particular, several experiments have shown that the initial grasp when acquiring an object is influenced by the subsequent planned actions so as to optimize *end-state comfort* [20]. Research in Human-Computer Interaction has never validated or tested these results, which suggest that we could possibly anticipate people's intentions as soon as they grab an object and before its actual manipulation starts.

Given that multitouch interaction techniques [5, 12, 28] usually simulate object manipulation in the physical world, we hypothesize that movement planning also takes place when users directly manipulate virtual objects with their hands. If this hypothesis is supported, we could possibly infer information about users' prospective movement to improve user experience during the manipulation phase. Interface designers could, for example, develop techniques that adapt their graphical layout to improve visual feedback, avoid potential occlusion issues [4, 25] or reduce interference [10] when multiple users interact in close proximity in collaborative settings. We could also derive directions about how to design grips and visual guides to facilitate both the acquisition and the manipulation of virtual objects.

We test this planning hypothesis by observing how people grasp objects prior to moving them to specific positions and orientations on a horizontal screen. We present three experimental studies that examine a simple two-dimensional docking task on the surface of a multitouch tabletop. The first experiment tests translation-only tasks. The second experiment tests rotation-only tasks. Finally, the third experiment examines tasks that combine both translational and rotational movements. The results of all the three experiments confirm the planning hypothesis. They show that the placement of the fingers at acquisition time is influenced by both the initial and the final state (position and orientation) of the virtual object. They also provide valuable information about how users grasp objects at different positions of a multitouch tabletop.

We analyze our results in the light of the *Weighted Integration of Multiple Biases* model [6], a very recent model in Psychology research. The model helps us to explain how the orientation of a user's initial grasp is influenced by a combination of several factors or *biases*, where each bias pulls the grasp orientation towards a certain orientation. We examine how our experimental results conform to this model. Finally, we discuss the design implications of our findings and identify several future directions. Our work focuses on multitouch tabletops but could serve as a framework for studying object manipulation in a larger range of user interfaces, including multitouch mobile devices and tangible interfaces.



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## RELATED WORK

### Manipulating Objects on Multitouch Surfaces

Previous work has studied a range of multitouch gestures for manipulating objects on interactive surfaces. Wu and Balakrishnan [28] defined a set of gestures that make use of both hands and multiple fingers. Among others, they demonstrated how to perform freeform rotations using the thumb and index finger. Moscovich and Hughes [17] proposed multi-finger interactions that allow users to control a larger number of degrees of freedom to translate, rotate, and deform an object in a single manipulation. Kruger et al. [12], on the other hand, proposed single-touch rotation and translation mechanisms relying on physics-based metaphors for manipulating objects. Hancock et al. have discussed advantages and disadvantages of different rotation and translation techniques [5]. Studies reported in [16, 27] have proposed sets of gestures defined by end-user elicitation methods and concluded that people prefer conceptually and physically simpler gestures than the ones created by HCI researchers. Finally, Hinrichs and Carpendale [8] examined how adults and children naturally interact with tabletops and observed significant variations among gestures of different users.

Discussing the properties of graspable user interfaces, Fitzmaurice and Buxton [3] identify two main phases of interaction: acquisition and manipulation. Although these two phases can be studied separately [3, 24], previous results [9] indicate that manipulation performance may depend on proper acquisition. Multitouch gestures are subject to the physical constraints imposed by the user's arm, wrist and finger joints. As a result, they can result in joint stress and discomfort. Hoggan et al. [9] studied the extent and comfort of $90°$ rotational movements at different locations on a horizontal surface starting from different angular postures. Lozano et al. [13] measured muscle activation using electromyography and observed that gestures involving two fingers can result in high levels of muscle activation. They concluded that "multitouch interaction has impact on the entire hand shoulder system and in some cases the impact can be at risk level".

### Planning when Manipulating Physical Objects

How people plan their acquisition and grasp to facilitate movement and optimize comfort has been the focus of a large body of work within the fields of Psychology and Motor Control. This work can be expressed using the notion of *orders of planning* [18]. Within that system, the last task in a sequence that influences the behavior defines the planning order. First order planning occurs when a grasp is influenced by the immediate task, for example the objects shape. Second order, when the grasp is influenced by the subsequent task, e.g., grasping an object to rotate or translate it to a given position, and so on. Research studying first order planning of grasp have revealed that the kinematics of the hand depend, for example, on the size, orientation, and shape [11, 22] of the object of interest.

Several studies have considered second or higher order planning. Marteniuk et al. [14] showed that the kinematics, i.e., the shape of a grasp, is influenced by the intended use of the object. Rosenbaum and colleagues have extensively studied how people orient their hand when grasping an object. They revealed that individuals favor initial hand placements that result in end positions that are either comfortable, i.e, optimize *end-state comfort* [19, 21], or yield the most control [20]. Short and Cauraught have corroborated these results [23]. This type of planning behavior is termed *prospective* movement control [1].

The above studies have mainly focused on discrete tasks where participants had to choose one of two grasps (e.g., grabbing a cylinder with the thumb up or down). Choosing one grasp yields an uncomfortable end position while the other one a comfortable, hence optimizes *end-state comfort*. However manipulating physical or user interface objects usually involves more continuous tasks.

Other studies, reviewed by Herbort [6], have examined continuous tasks, in particular rotations of physical knobs for a range of angles. Their results suggest that *end-state comfort* planning alone cannot sufficiently explain the observed grasp selection in such tasks. Herbort [6] argues that it is unclear how precisely someone can anticipate a final posture of a movement and its associated costs, and therefore, optimal planning may not always be feasible. To account for the various *biases* that determine a grasp selection, he proposes the *Weighted Integration of Multiple Biases* (WIMB) model [7]. In its simplest form, the model can be expressed as follows:

$$p_{initial} = \frac{w_{anti} \cdot p_{anti} + w_{default} \cdot p_{default}}{w_{anti} + w_{default}} \quad (1)$$

According to the model, two different biases contribute to the initial grasp orientation $p_{initial}$. An anticipatory bias pulls the initial grasp toward a pronated or supinated angular position $p_{anti}$, depending on the intended direction of rotation. A second bias pulls the initial grasp toward a preferred task-independent orientation $p_{default}$. The contributing weights $w_{anti}$ and $w_{default}$ of the two biases can vary, for example, depending on the difficulty of the task or the required end precision. The above model can be extended with additional bias terms, such as one that accounts for the effect of previous movements in a sequence of tasks that involve different rotation directions and angles [6].

To the best of our knowledge, HCI research has never validated or tested the above results. The most relevant contribution in this direction belongs to Möllers et al. [15]. They tested the hypotheses of a predecessor and a successor (i.e., a planning) effect on the offset and angle of a touch point in a sequence of pointing tasks. They observed that finger posture is influenced by the previous pointing action but not by the next pointing action. This suggests that prospective control does not occur in this specific pointing case.

## GOALS AND APPROACH

Our hypothesis is that movement planning plays a determinant role in tabletop interaction as movements extend to a large space and object manipulation involves the coordination of multiple limbs, often in constrained positions and postures. Our goal was to test this hypothesis but also understand and

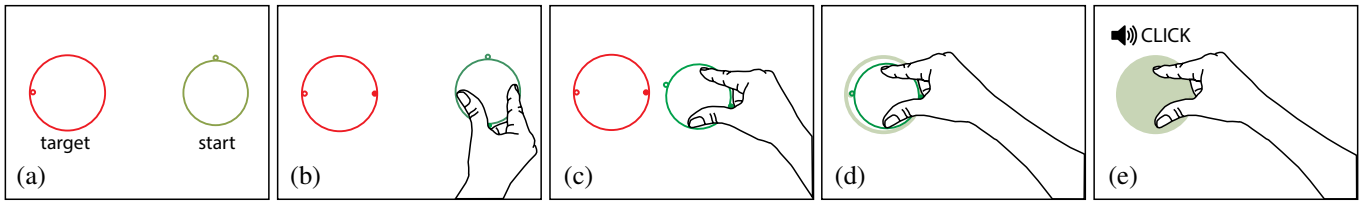


**Figure 1. Experimental task scenario: The task requires the user to (b) grab the green object with the thumb and the index finger, (c) move it towards the red target and then align it with it, and (d) hold the object in the target for 600 ms to (e) complete the task.**

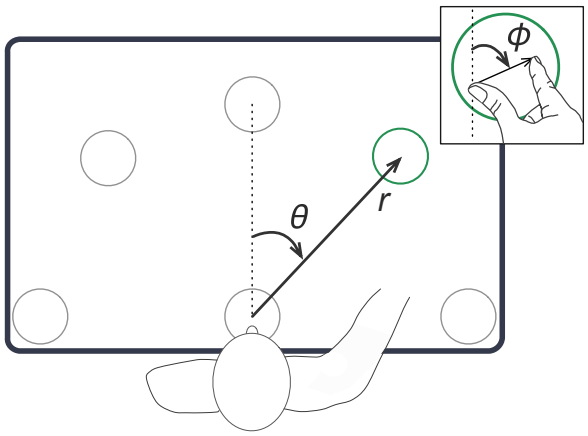


**Figure 2. The position of interactive objects expressed in polar coordinates $(r, \theta)$, where $r$ is the radial distance and $\theta$ is the clockwise angle with respect to the vertical axis of the screen. The grip orientation is expressed by the clockwise angle $\phi$ defined by the thumb and the index.**

describe how planning affects how users grasp virtual objects to facilitate their manipulation.

We conducted three experiments. The experiments tested unconstrained translation and rotation tasks on different locations of a multitouch surface. As opposed to Hoggan et al. [9] who express screen location in $x$ and $y$ coordinates, we use a polar coordinate system and express the location of an object in terms of its distance $r$ and angle $\theta$ with respect to the front-center of the screen, close to where the user stands (see Figure 2). This design configuration was driven from the observation that the orientation of a neutral hand posture changes in circular manner around the user. Although the polar coordinate system presented in Figure 2 is not an accurate representation of the user's biomechanical coordinate system, it offers a reasonable approximation and simplifies data analysis. As we see later in this paper, our approach allows for better experimental control and a simpler interpretation of the observed grasp orientations. As Hoggan et al. [9], we focus on one-hand two-finger interaction, where objects are grasped and rotated with the thumb and the index finger (Figures 1-2).

Our studies are mostly inspired by the continuous-tasks approach [6, 7] rather than discrete-tasks approach of Rosenbaum et al. [18, 19, 20]. The former is more generic and can describe situations with uncertainty about the final grasp orientation of a movement and the costs associated with a certain object acquisition strategy. In such cases, optimal planning is difficult or even impossible. We analyze our data in the light of the WIMB model [6], which predicts the initial grasp orientation given the anticipatory target-orientation bias and the default task-independent orientation bias (see Equation 1). The WIMB model was based on results from pure rotation tasks with tangible objects. Here, we examine translation in addition to rotation.

## EXPERIMENTAL METHOD

The task of all the three experiments consists of grasping and moving an object. Each experiment, however, focuses on a different movement component. In Experiment 1, we test a translation task where participants have to change the position of the object while keeping its initial orientation. Experiment 2 involves rotations, requiring participants to change the objects' orientation but not their position. In Experiment 3, we combine translations and rotations so participants need to both change the position and orientation of the object.

### Apparatus

The experiments were performed on a 3M Multi-Touch Display C3266P6 with $698.4 \times 392.85$ mm display area, a refresh rate of 120 Hz, and a native resolution of $1920 \times 1080$. The display was placed flat on a table in landscape orientation, resulting in the multitouch surface to be at a height of 95 cm. A digital video camera on a tripod above the display monitored the participant's hand and arm movements.

The experimental software was developed in Java 2D (JDK 6) and ran on a Macbook Pro 2.66 GHz Intel Core i7 with 4GB memory, running Mac OS X 10.6.8. Touch noise was reduced with a complementary filter.

### Common Task Features

Figure 1 illustrates a typical scenario for our experimental tasks. In all three experiments the touch display shows a circular *start* object, which can be moved and rotated, and a static circular *target*. The *start* object is green and has a diameter of 60 mm. The *target* object is red and has a diameter of 70 mm. To start a trial the user presses a touch button at the bottom half of the display. The user has then to grab the *start* object with the thumb and the index of the right hand and manipulate it to make its position and orientation match the *target*. The user can freely translate and rotate but not resize the object. Translations follow displacements of the center of the segment connecting the touch points of the two fingers. Rotations follow changes in the angular position of this segment. The orientation of both object and target are indicated by a handle (small open circles). Grasping the *start* object triggers the appearance of a secondary handle (small

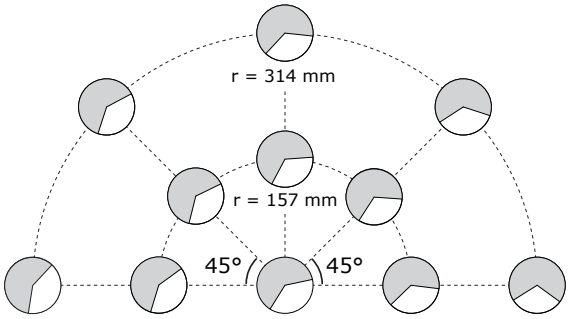


**Figure 3. Extreme range of grip angles for various tabletop positions. Average ranges for the right hand of 10 right-handed participants.**

closed circles) located $180°$ from the primary (Figure 1-b). To complete a task the *start* object has to be held in the *target* for $600$ ms. The precision tolerance for placing the object into the target is $\pm 5°$ in angular direction and $5$ mm in diameter. The angular positions ($\theta_{start}$ and $\theta_{target}$) of objects, their radial distances ($r_{start}$ and $r_{target}$) and their rotation angles $\beta$ are specific to each experiment and will be detailed later.

The user interface provides visual feedback to indicate that the object was correctly placed into the target. It also provides visual and audio feedback to inform the user about the completion of the task and errors, which occur when the user lifts a finger before task completion.

### Procedure

Prior to each experiment, participants had to wash their hands and dry carefully in order to minimize screen friction and facilitate object sliding. Participants were positioned standing at the center of the long side of the display and were not allowed to walk. The operator asked them to only use the thumb and the index finger of the right hand to interact with the object, while keeping their left hand down by their side. Participants were not explicitly encouraged to plan their grasps and were not aware of the experimental goals. They were instructed not to rush and avoid errors.

### Measures

We recorded detailed information about the position of the fingers on the multitouch screen and their movements. Our two main dependent variables are:

1. The initial grasp orientation $\phi_{init} \in [-180°, 180°]$, measured as the clockwise angle between the vertical axis and the vector from the thumb to the index finger (see Figure 2). Our 3M multitouch display could not differentiate between fingers. We derived the correct grasp orientation from the range of attainable grasp orientations, measured at each screen position in a pre-study with 10 participants (see Figure 3). We also used detailed logs and recorded video to ensure that grasp orientation was derived correctly.

2. The default task-independent grasp orientation $\phi_{default} \in [-180°, 180°]$ for each position of the display. To measure it, we only consider trials where *start* and *target* configurations are the same.

We also measure $ErrorRate$ and the reaction time $RT$ participants need to plan their grasp before touching the screen.

### Hypotheses

We hypothesize that $\phi_{init}$ is determined by both the *start* and *target* object configurations. We expect that planning will occur for both rotational and translational movements. Since the orientation of ergonomic hand gestures changes along different locations of the tabletop [9], we predict that users will plan appropriately in order to reduce the occurrence of uncomfortable end-postures. Influenced by the WIMB model [6], we hypothesize that $\phi_{init}$ will be affected by three factors of postural bias: $\phi_{default}$ of the *start* position, $\phi_{default}$ of the *target* position, and the object's angle of rotation $\beta$.

## EXPERIMENT 1: TRANSLATIONS

We first tested translation tasks, where participants had to grab and move an object, keeping its initial orientation.

### Participants

Twelve volunteers (four women and eight men), 23 to 32 years old, participated in the experiment. All were right-handed and had normal or corrected-to-normal vision.

### Task and Conditions

We tested six screen positions for both the *start* and the *target* objects. One was located close to the user, centered on the vertical axis of the display, 35 mm from the front edge. We refer to it as the *User* position. The other five positions were located around the *User* position with an angular position $\theta_{start}$ of $-90°$, $-45°$, $0°$, $45°$, and $90°$, and a radial distance of $r = 314$ mm. The *start* and the *target* objects could appear at the same position. In this case, the user should hold the *start* object and keep it inside the *target*.

To test whether and to what extent planning occurs for translation tasks, there were two main conditions:

*Known Target.* The *target* appears with the *start* object at the beginning of the task. Users are aware of the end position of their movements, and therefore, they can plan the orientation of their grasps.

*Hidden Target.* This is a control condition. The *target* is initially hidden. It appears after the user acquires the *start* object. Thus, users cannot plan the orientation of their grasp.

### Design

We followed a within-participants full-factorial design, which can be summarized as follows:

12 participants
$\times$ 2 Conditions (*Known*, *Hidden Target*)
$\times$ 2 Blocks
$\times$ 6 $\theta_{start}$ (*User*, $-90°$, $-45°$, $0°$, $45°$, $90°$)
$\times$ 6 $\theta_{target}$ (*User*, $-90°$, $-45°$, $0°$, $45°$, $90°$)
$\times$ 3 Replications

$= 5184$ tasks in total

In addition, participants completed 15 practice tasks for each condition. The order of presentation of the two conditions

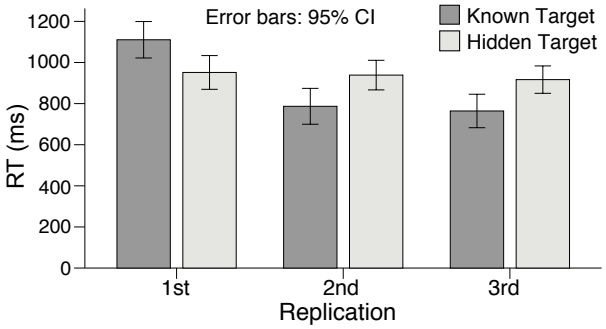


**Figure 4. Mean reaction time for each of the three task replications**

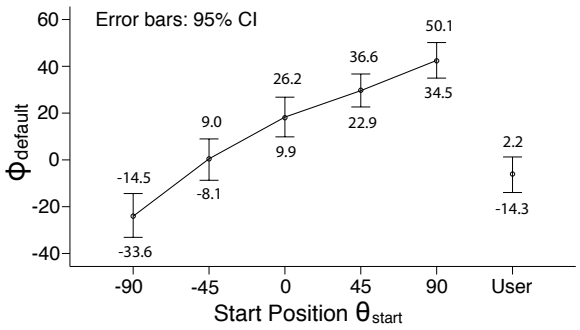


**Figure 5. The default grasp orientation $\phi_{default}$ at each position $\theta_{start}$**

was fully balanced among participants. Start and target positions were randomized within each block. Tasks were grouped by three but in a different way for each condition. In the *Known Target* condition, groups contained the three replications of the same task, allowing participants to re-plan and possibly revise their grasp orientation. In case of an error, the participant had to restart the task. In the *Hidden Target* condition, groups contained a random selection of tasks. When an error occurred, the task was not repeated immediately. It was moved to the end of the block and was replaced by the following in the list. This design eliminates planning effects for this condition. Experimental sessions lasted 50 to 60 minutes.

## Results

For error comparisons, we used the Wilcoxon signed-rank test. For *RT*, we conducted a 5-way Repeated Measures (RM) ANOVA with the complete set of factors. For $\phi_{default}$, we conducted a 3-way ANOVA, where we included only *Known Target* tasks for which $\theta_{target}$ was identical to $\theta_{start}$. Finally, for $\phi_{init}$, we split our data into three sets:

1. PERIPHERY: The *start* and *target* objects are at the periphery of the display.
2. OUTWARD: The *start* object is close to the user.
3. INWARD: The *target* object is close to the user.

We conducted a 5-way RM ANOVA for the first set and 4-way RM ANOVAs for the second and third set, as the factors $\theta_{start}$ and $\theta_{target}$, respectively, were not relevant for these sets. We only report on main effects and two-factor interactions that are meaningful and relevant to our hypotheses. When possible, we use a 95% confidence interval (CI) [2] to report on the estimated difference between two means.

### *Errors*

$ErrorRate$ was 3.6% ($SD = 1.9\%$) and 5.3% ($SD = 3.5\%$) for *Known* and *Hidden* targets, respectively. Yet, this difference was not statistically significant ($Z = -1.37$, $p = .17$). Interestingly, leftward movements, starting from the right half (45°, 90°) and ending to the left half (−45°, −90°) of the display resulted in more errors than rightward movements ($Z = -3.06$, $p = .002$). Their error rate was 15.3% ($SD = 7.8\%$) compared to a 3.0% ($SD = 4.0\%$) of the exact opposite movements. We believe that there are two causes of this difference. First, fingers of the right hand may produce more friction when moved leftwards. Second, the right arm is more constrained by the user's body when moving leftwards. Similarly, we found that outward movements starting close to the user produced more errors than the reverse inward movements ($Z = -2.32$, $p = .021$), where $ErrorRate$ was 6.4% ($SD = 3.8\%$) and 3.5% ($SD = 3.1\%$), respectively. We believe that increased finger friction and movement constraints due to the anatomy can also explain this difference.

### *Reaction Time*

*RT* was not significantly different between *Known* and *Hidden* targets (CI: [−112 ms, 15 ms], $p = .12$). However, we found a significant interaction *Condition* × *Replication* ($F_{2,22} = 76.78$, $p < .001$). Figure 4 presents the estimated mean values. The results suggest that planning only occurred for the first instance of each series of replicated tasks.

### *Grasp Orientation*

$\theta_{start}$ had a significant effect on the default grasp orientation $\phi_{default}$ ($F_{2.2,23.9} = 84.79$, $p < .001$)[1]. Figure 5 presents how $\phi_{default}$ varied along different angular positions.

PERIPHERY. $\phi_{init}$ was not significantly different between *Known* and *Hidden* targets (CI: [−9.9°, 2.5°], $p = .22$). However, the interaction *Condition* × $\theta_{target}$ was significant ($F_{4,44} = 13.25$, $p < .001$), which indicates a planning effect. We found a significant main effect of both $\theta_{start}$ ($F_{1.2,12.8} = 71.24$, $p < .001$) and $\theta_{target}$ ($F_{1.9,21.0} = 12.83$, $p < .001$). Surprisingly, *Replication* did not significantly affect the grasp ($F_{2,22} = 1.51$, $p = .242$). This seconds our results on response time for *Known Target*: participants planned their grasp for the first task in the group but did not refine it after. As shown in Figure 6, $\phi_{init}$ was mainly determined by the *start* position. The *target* position contributed less, mainly for target positions at the left half of the display.

INWARD. Again, $\phi_{init}$ was not significantly different between *Known* and *Hidden* targets (CI: [−5.2°, 2.1°], $p = .36$). The effect of $\theta_{start}$ was significant ($F_{1.6,17.2} = 37.90$, $p < .001$). However, *Condition* × $\theta_{start}$ was only marginally significant ($F_{12.2,24.5} = 3.15$, $p = .056$). As shown in Figure 6, planning only occurred as a slight bias towards lower grasp angles for *start* positions at the right half of the display.

[1]When sphericity is violated, the degrees of freedom have been corrected by using Greenhouse-Geisser correction.

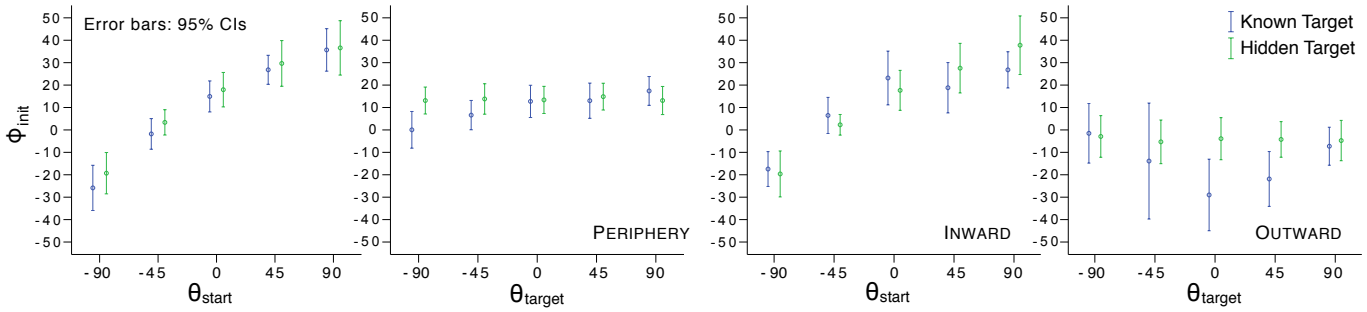


**Figure 6. Experiment 1: Effect of start $\theta_{start}$ and target $\theta_{target}$ angular positions on $\phi_{init}$ for peripheral, inward and outward translations**

OUTWARD. $\phi_{init}$ was significantly lower for *Known Target* (CI: $[-18.1°, -2.9°]$, $p = .011$). The effect of $\theta_{target}$ was significant ($F_{2.0,22.0} = 4.66$, $p = .02$), as was the interaction *Condition* $\times$ $\theta_{target}$ ($F_{1.7,18.7} = 4.34$, $p = .033$). Figure 6 shows that planning occurred, but not as expected. The orientation bias added by the *target* positions $\theta_{target}$=0° and $\theta_{target}$=45° has a direction opposite to the one suggested by their default orientations (see Figure 5). This means that participants chose a grasp away from both the start and end-state comfort position. For the $-45°$ target position, results are more unclear because different participants chose different strategies. Our interpretation is that comfort is not always determined by the start and end state of the movement. As the arm and hand have multiple segments and joints that need to coordinate in order to accomplish a movement, transitions between intermediate states can play an important role. In this particular case, we observed that participants adapted their grasp to optimize the flow of their movement.

## EXPERIMENT 2: ROTATIONS

The second experiment tested pure rotation tasks that are closer to the physical rotation tasks reviewed by Herbort [6].

### Participants

Twelve volunteers (four women and eight men), 22 to 46 years old, participated in the experiments. Three had also participated in Experiment 1. All were right-handed and had normal or corrected-to-normal vision.

### Task

Participants performed rotations in two directions $\beta_{dir} \in \{clockwise, counterclockwise\}$. Rotations $\beta$ had three levels: 40°, 80°, 120°. As the task did not involve translations, the *start* and *target* positions overlapped. We tested the same angular positions $\theta$ as in Experiment 1 but added a closer radial distance $r = 157$ mm. We discarded the $User$ position, as rotational movements are uncomfortable when the hand is too close to the body.

Contrary to Experiment 1, the *target* object was always displayed. Our pilot tests showed that completing the most difficult tasks ($\beta \geq 80°$) with no previous knowledge of the *target* was hard or impossible.

### Design

We followed a within-participants full-factorial design, which can be summarized as follows:

12 participants
$\times$ 3 Blocks
$\times$ 5 $\theta$ ($-90°$, $-45°$, 0°, 45°, 90°)
$\times$ 2 $r$ (157 mm, 314 mm)
$\times$ 2 $\beta_{dir}$ ($clockwise$, $counterclockwise$)
$\times$ 3 $\beta$ (40°, 80°, 120°)

$=$ 2160 tasks in total

Prior to the experiment, participants completed 15 practice tasks. The order of tasks within each block was randomized. The experiment took approximately 20 minutes to complete.

### Results

For error comparisons, we used the Wilcoxon signed-rank (2 related samples) or the Friedman test ($k$ related samples). For *RT* and $\phi_{init}$, we conducted full 5-way RM ANOVAs.

#### *Errors*

The angle of rotation $\beta$ had a significant effect on errors ($\chi^2(2) = 11.35$, $p = .003$). *ErrorRate* was 3.5% ($SD = 3.7\%$), 2.6% ($SD = 2.4\%$), and 6.4% ($SD = 3.3\%$) for 40°, 80°, and 120°, respectively. Differences were significant between 40° and 120° ($p = .024$) and between 80° and 120° ($p = .013$). *ErrorRate* was 4.6% ($SD = 3.0\%$) for clockwise and 3.6% ($SD = 3.2\%$) for counterclockwise rotations, but this difference was not significant ($Z = -1.03$, $p = .31$).

#### *Reaction Time*

The mean *RT* was 1057 ms. It was significantly longer (CI: [6 ms, 157 ms], $p = .038$) for clockwise than for counterclockwise rotations. Larger angles also took longer to plan ($F_{2,22} = 20.80$, $p < .001$). More specifically, 120° rotations took 208 ms (CI: [120 ms, 269 ms]) more than 40° rotations ($p = .001$) and 151 ms (CI: [75 ms, 226 ms]) more than 80° rotations ($p = .003$). *Block* did not have any significant effect on *RT* ($F_{2,22} = .51$, $p = .61$), i.e., no learning occurred.

#### *Grasp Orientation*

$\phi_{init}$ was significantly higher for counterclockwise rotations (CI: $[21.1°, 27.5°]$, $p < .001$). The effects of $\beta$ ($F_{1.4,15.2} = 20.76$, $p < .001$) and the interaction $\beta_{dir} \times \beta$ ($F_{1.1,12.5} = 50.76$, $p < .001$) were also significant. As shown in Figure 7, the effect of clockwise rotations was more pronounced. This result is not surprising. It can be explained by the fact that the right range of grasp orientations, which is used for the planning of counterclockwise rotations, is more constrained compared to the the left range of orientations (see Figure 3).

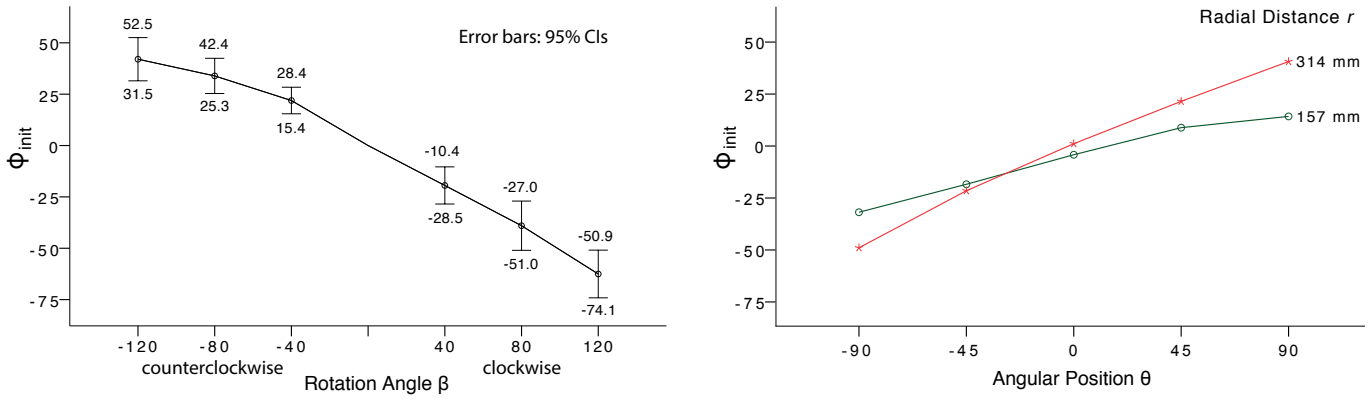


**Figure 7. Experiment 2: Effects of the rotation angle $\beta$ and the angular position $\theta$ on the grip orientation $\phi_{init}$**

Figure 7 illustrates the effects of $\theta$ ($F_{1.6,17.4} = 257.84$, $p < .001$), $r$ ($F_{1,11} = 23.13$, $p < .001$), and $\theta \times r$ ($F_{2.3,25.5} = 42.26$, $p < .001$). The effect of $\theta$ decreases as $r$ becomes shorter, and we can expect that it converges to zero as interaction approaches the user's position. Finally, we found no learning effects. The main effect of *Block* was not significant ($F_{2,22} = 1.68$, $p = .21$) and neither was its interaction with other factors ($p > .7$).

## EXPERIMENT 3: TRANSLATIONS AND ROTATIONS

Experiments 1 and 2 showed planning effects for both translations and rotations. Experiment 3 tests how users plan their grasp orientation in preparation to more complex tasks where rotation and translation occur in parallel.

### Participants and Task

This study involved the same participants as Experiment 2. We tested six *start* and *target* positions, where $\theta_{start}$, $\theta_{target} \in \{-60°, 0°, 60°\}$ and $r_{start}, r_{target} \in \{157 \text{ mm}, 314 \text{ mm}\}$. In addition to these positions that define the translational movement component, we tested three angles of rotation $\beta \in \{-90°, 0°, 90°\}$.

### Design

We followed a within-participants full-factorial design:

12 participants
$\times$ 3 Blocks
$\times$ 3 $\theta_{start}$ $(-60°, 0°, 60°)$ $\times$ 2 $r_{start}$ (157 mm, 314 mm)
$\times$ 3 $\theta_{target}$ $(-60°, 0°, 60°)$ $\times$ 2 $r_{target}$ (157 mm, 314 mm)
$\times$ 3 $\beta$ $(-90°, 0°, 90°)$

$=$ 3888 tasks in total

Participants performed 15 practice tasks prior to the experiment. The order of tasks within each block was randomized and the experiment took 30-35 minutes to complete.

### Results

For errors, we used the Wilcoxon signed-rank and the Friedman tests. For *RT* and $\phi_{init}$, we conducted full 6-way RM ANOVAs. For $\phi_{default}$, we conducted a 3-way RM ANOVA, where $\theta_{target} = \theta_{start}$, $r_{target} = r_{start}$, and $\beta = 0$.

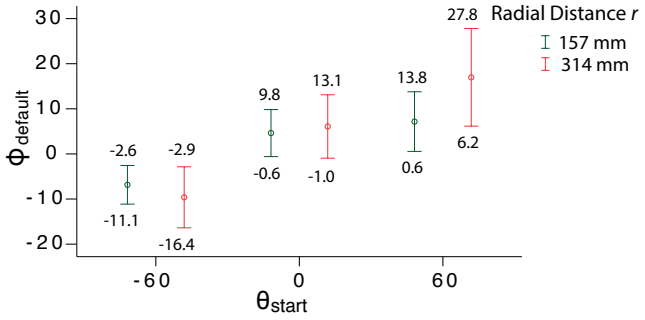


**Figure 8. Experiment 3: $\phi_{default}$ in different screen locations**

#### *Errors*

*ErrorRate* was 5.5% ($SD = 3.5\%$). As in Experiment 1, leftward movements produced more errors ($Z = -2.10$, $p = .036$). More specifically, *ErrorRate* for movements starting from 60° and ending at −60° was 12.0% ($SD = 11.2\%$) compared to a 4.6% ($SD = 4.6\%$) for the reverse movements. *ErrorRate* for outward and inward movements was 8.7% ($SD = 7.1\%$) and 4.0% ($SD = 4.1\%$), respectively, but this difference was not significant ($Z = -1.91$, $p = .056$). Similarly, the effect of the rotation angle $\beta$ was only marginally significant ($\chi^2 = 5.91$, $p = .052$).

#### *Reaction Time*

The effect of $\beta$ was significant ($F_{2,22} = 11.57$, $p < .001$). Clockwise rotations were again 60 ms longer (CI: [12 ms, 107 ms], $p = .019$) to plan than counterclockwise rotations, increasing *RT* from 1068 to 1128 ms. The effect of *Block* was significant ($F_{1.2,13.3} = 8.25$, $p = .01$) for this experiment. The increased task difficulty could explain this result.

#### *Grasp Orientation*

Figure 8 presents our results for the default grasp orientation $\phi_{default}$. We found a significant effect of both $\theta_{start}$ ($F_{1.3,14.0} = 18.24$, $p < .001$) and its interaction $\theta_{start} \times r_{start}$ ($F_{2,22} = 7.04$, $p = .004$). As in Experiment 1, $\phi_{default}$ increases with $\theta_{start}$. The effect is stronger for distant ($r = 314$ mm) than for close objects ($r = 157$ mm).

We then analyzed the initial grasp orientation $\phi_{init}$. We found significant effects for $\theta_{start}$ ($F_{1.3,14.7} = 81.9$, $p < .001$), $r_{start}$

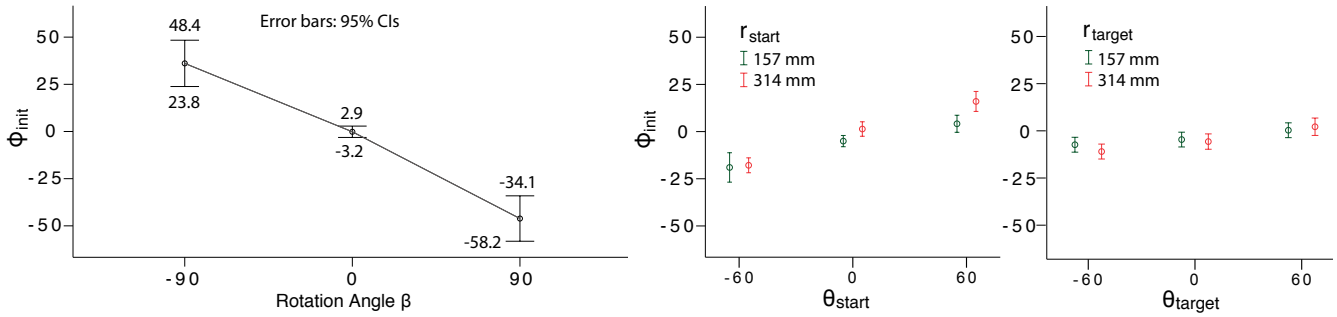


**Figure 9. Experiment 3: Effects of the rotation angle $\beta$, the start position $\theta_{start}$ and the target position $\theta_{target}$ on the grip orientation $\phi_{init}$**

($F_{1,11} = 26.73$, $p < .001$), and $\theta_{target}$ ($F_{1.4,15.2} = 27.19$, $p < .001$). The effect of $r_{target}$ was not significant ($F_{1,11} = 3.25$, $p = .099$). However, its interaction $r_{target} \times \theta_{target}$ was significant ($F_{2,22} = 8.44$, $p = .002$), as was the interaction $r_{start} \times \theta_{start}$ ($F_{2.5,27.4} = 5.96$, $p = .004$). Overall, grip adaptation was more pronounced for distant positions ($r = 314$ mm). Figure 9 illustrates these effects. Results are consistent with the findings of Experiment 1. Participants adapted their grasp orientation based on both the *start* and the *target* position of their movement. Again, the bias of the *start* position was stronger than the bias of the *target* position.

Finally, the effect of the rotation angle $\beta$ was significant ($F_{1.1,11.7} = 61.43$, $p < .001$). As shown in Figure 9, results follow closely results of Experiment 2. Participants anticipated how to adapt their initial grasp despite to the translation movement that occurred in parallel with the rotation task. As in Experiment 2, we did not observe any learning effect.

## SYNTHESIS OF FINDINGS

Our results support our hypothesis, being in accordance with the general principles of Herbert's WIMB model for physical objects [6]. Users plan their grasp orientation in preparation for the manipulation of virtual objects. Planning takes place under the influence of several biases that include at least a *task-independent preferred bias* and an *anticipatory bias*. When planning is not possible, as in the *Hidden target* condition of experiment 1, participants adopt the strategy of using a "standard" initial grip for all target positions (see Figure 6).

In all the three experiments, we found that the initial grasp orientation $\phi_{init}$ is influenced by both the *start* and *target* configurations. Experiment 1 showed that users adapt their $\phi_{init}$ to account for the difference between the *start* and *target* value of $\phi_{default}$, which varies across distant angular positions (see Figures 5 and 8). Experiment 2 showed that users adapt their $\phi_{init}$ in preparation for rotations so that they do not end up in uncomfortable positions. Experiment 3 examined both translations and rotations and showed that both of the above effects occur in parallel, with planning for rotations having a stronger effect. Finally, we observed that in special cases the *start* and *target* configurations are not the only factors to affect grasp orientation. In Experiment 1, *Outward* tasks, participants used noticeably different planning strategies for the $-45°$ target position, demonstrated by the large confidence interval of $\phi_{init}$ (see Figure 6). Some participants chose to "push" the object with a positive $\phi_{init}$ while others preferred to "pull" it using a negative $\phi_{init}$. This suggests that in some situations, different planning strategies can be appropriate for the same task. We plan to further investigate this observation in future work.

As the studies reviewed by Herbert [6] considered only rotational tasks, we can check if our results of rotations fit the same formal model. Figure 10 presents the results of Experiment 2 through WIMB's mathematical formulation (see Equation 1) for $r = 317$ mm. We have normalized the initial and default grasp orientations by setting $p_{init} = \phi_{init} - \phi_{default}$ and $p_{default} = 0$, where the default orientations $\phi_{default}$ are the values measured by Experiment 1. Following Herbert's [6] approach, we examine clockwise and counter-clockwise rotations separately. Our results are consistent with previous results on the manipulation of physical objects, summarized in his survey. As WIMB predicts, we observe that users tend to compensate small angles proportionally more than large ones. We also observe that the effect of the anticipatory bias is stronger for clockwise rotations. We hypothesize that this is due to the fact that the range of motion is smaller in clockwise than counter-clockwise direction at most screen positions (see Figure 3). When a task involves a clockwise rotation, participants are required to do a larger (than if the task was a counter-clockwise rotation) preparatory rotation in the opposite direction to avoid uncomfortable or even impossible hand and arm positions. This asymmetry in movement direction may also explain why we observe a longer planning time (i.e., reaction time) for clockwise rotations in Experiments 2 and 3.

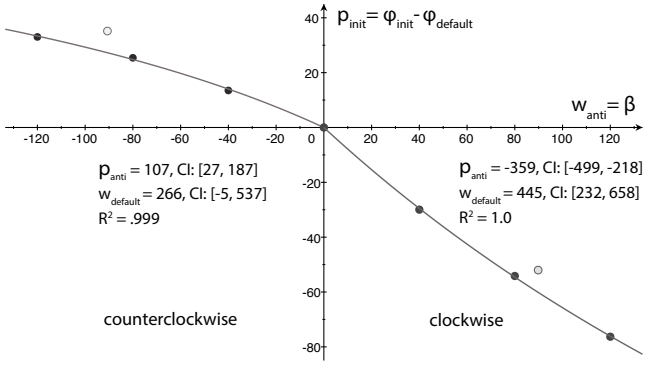


**Figure 10. The WIMB model for Experiment 2, when $r = 314$ mm. We assume that $p_{default} = 0$. The empty circles show the results of Experiment 3 for simple only rotations.**

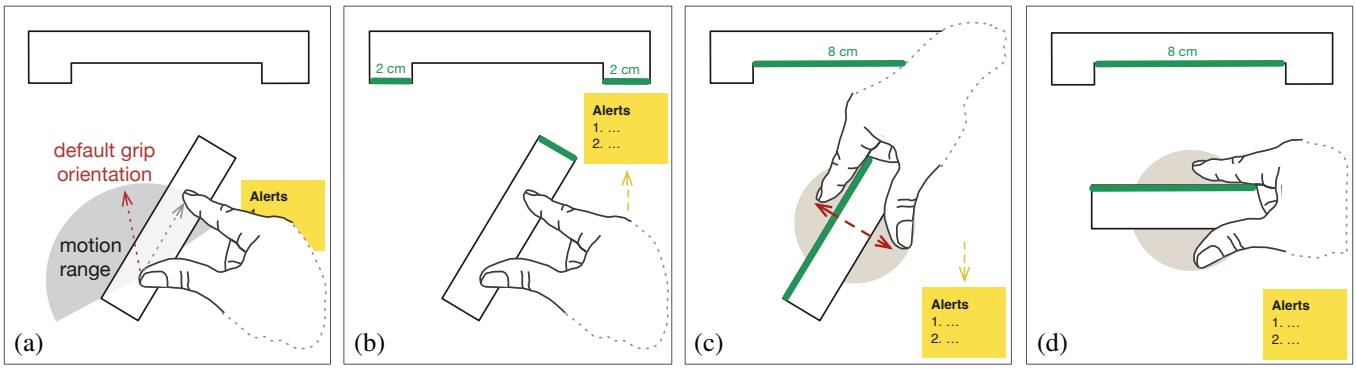


**Figure 11. Using movement planning to improve feedback and prevent occlusion in an object-matching scenario. (a) The user acquires an object along its main graspable axis. (b) The system anticipates an anticlockwise rotation and indicates exact matches between its short edge and edges of the top object. The "alerts" box moves upwards, avoiding hand occlusion. (c) A pinch gesture over the object creates a circular grip that allows the user to grasp and rotate it clockwise. The system anticipates the planned rotation and indicates matches of it long edge. It also moves the "alerts" box downwards to minimize occlusion during the manipulation of the object. (d) The user has rotated the object in order to move it to the hole of the object at the top.**

Finally, we found that clockwise rotations were more error prone than counterclockwise rotations. These results are in agreement with the results of Hoggan et al. [9] who concluded that performance is significantly inferior for clockwise rotations. The planning effect we observe in our experiment seems to be at odds with those of Möllers et al. [15], which did not observe prospective planning in a sequential pointing task on a multi-touch screen. However, looking closer at their task, we can see that comfort plays a minor role while *start* and *target* finger orientations are not constrained by each other. We suspect that movement planning in this case adds cognitive overhead without necessarily aiding the task.

## IMPLICATIONS AND FUTURE DIRECTIONS

Our results open a new space for innovation with design implications for several application scenarios. First, they can inform the design of the form and affordances of virtual objects around a tabletop. Different surface positions are associated with different ranges of motion and different default grasps. Designers can make use of this information to appropriately position objects on the surface or design grips and interaction techniques that facilitate grasping (Figure 11-c).

Getting knowledge about the planned movement early enough when the user acquires an objet can be also valuable for improving user experience during its manipulation. We are particularly interested in exploring the design of new occlusion-aware techniques [4, 25]. Enhancing existing hand-occlusion models for multitouch [25] with a movement-planning model could possibly provide more reliable estimation about the occluded areas at acquisition time or during manipulation. Such information could be useful for optimizing the display of feedback and visual content at visible locations of the screen. It could be also useful for improving motor control, e.g., by avoiding object snapping around positions that are away from predicted targets. We do not encourage designs that make blind use of such predictions, as this could be the source of user frustration in case of false predictions. Figure 11 illustrates a simple scenario where movement planning is used to optimize visual feedback and reduce hand occlusion.

Our results could be also useful in collaborative scenarios where spatial interference and conflicts between the actions of collaborators are frequent [10]. We can foresee conflict-resolution techniques that make use of information about prospective movement. In addition, when users organize pieces of information collaboratively, the system could detect potential relationships between objects located in different personal workspaces and assist users with appropriate visual feedback. For example, it could display handles around an object that suggest a grasp and thus a specific movement that would bring this object close to other related ones.

Finally, we are interested in studying the role of movement planning for other multitouch devices, such as tablets, especially in connection with how users grasp and hold them [26]. Future work also needs to explore its implications for tangible user interfaces, where grasping and acquisition are determinant factors of user performance [3, 24].

## CONCLUSION

Translational and rotational tasks are manipulations commonly performed on multitouch tabletops. We have investigated whether prospective planning is present when people perform such manipulations. We have shown that users choose a grip orientation that is influenced by three factors: (1) a preferred orientation defined by the start object position, (2) a preferred orientation defined by the target object position, and (3) the anticipated object rotation. We have examined these results in the view of the WIMB model, which has been recently introduced by Herbort [6] to explain planning for the manipulation of physical objects. We have shown that our results are consistent with the WIMB model.

We have also shown that relative to the geometry of the tabletop, upwards, leftwards movements and clockwise rotations are more difficult for users to perform. While the effects of planning on interaction with multitouch interfaces are not yet fully understood, our results provide a first look at a phenomenon that should be taken into account when designing tabletop applications.

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## REFERENCES


1. Cohen, R. G., and Rosenbaum, D. A. Prospective and retrospective effects in hulman motor control: planning grasps for object rotation and translation. *Psychological Research 75*, 4 (2011), 341–349.
2. Cumming, G., and Finch, S. Inference by eye: confidence intervals and how to read pictures of data. *American Psychologist 60*, 2 (2005), 170–180.
3. Fitzmaurice, G. W., and Buxton, W. An empirical evaluation of graspable user interfaces: towards specialized, space-multiplexed input. In *Proc. CHI '97*, ACM (1997), 43–50.
4. Hancock, M. S., and Booth, K. S. Improving menu placement strategies for pen input. In *Proc. GI '04*, Canadian Human-Computer Communications Society (2004), 221–230.
5. Hancock, M. S., Carpendale, S., Vernier, F. D., Wigdor, D., and Shen, C. Rotation and translation mechanisms for tabletop interaction. In *Proc. TABLETOP '06*, IEEE Computer Society (2006), 79–88.
6. Herbort, O. Optimal versus heuristic planning of object manipulations: A review and a computational model of the continuous end-state comfort effect. *New Ideas in Psychology* (2013), 1–11.
7. Herbort, O., and Butz, M. The continuous end-state comfort effect: weighted integration of multiple biases. *Psychological Research 76*, 3 (2012), 345–363.
8. Hinrichs, U., and Carpendale, S. Gestures in the wild: studying multi-touch gesture sequences on interactive tabletop exhibits. In *Proc. CHI '11*, ACM (2011), 3023–3032.
9. Hoggan, E., Williamson, J., Oulasvirta, A., Nacenta, M., Kristensson, P. O., and Lehtio, A. Multi-touch rotation gestures: Performance and ergonomics. *Proceedings of CHI 2013* (2013), 3047–3050.
10. Hornecker, E., Marshall, P., Dalton, N. S., and Rogers, Y. Collaboration and interference: awareness with mice or touch input. In *Proc. CSCW '08*, ACM (2008), 167–176.
11. Jeannerod, M. The timing of natural prehension movements. *Journal of motor behavior 16*, 3 (1984), 235–254.
12. Kruger, R., Carpendale, S., Scott, S. D., and Tang, A. Fluid integration of rotation and translation. In *Proc. CHI '05*, ACM (2005), 601–610.
13. Lozano, C., Jindrich, D., and Kahol, K. The impact on musculoskeletal system during multitouch tablet interactions. In *Proc. CHI '11*, ACM (2011), 825–828.
14. Marteniuk, R. G., MacKenzie, C., Jeannerod, M., Athenes, S., and Dugas, C. Constraints on human arm movement trajectories. *Canadian Journal of Psychology 41*, 3 (1987), 365–378.
15. Möllers, M., Dumont, N., Ladwig, S., and Borchers, J. Improving touch accuracy on large tabletops using predecessor and successor. In *Proc. CHI '13*, ACM (2013), 755–758.
16. Morris, M. R., Wobbrock, J. O., and Wilson, A. D. Understanding users' preferences for surface gestures. In *Proc. GI '10*, Canadian Information Processing Society (2010), 261–268.
17. Moscovich, T., and Hughes, J. F. Multi-finger cursor techniques. In *Proc. GI '06*, Canadian Information Processing Society (2006), 1–7.
18. Rosenbaum, D. A., Chapman, K. M., Weigelt, M., Weiss, D. J., and van der Wel, R. Cognition, action, and object manipulation. *Psychological Bulletin 138*, 5 (2012), 924–946.
19. Rosenbaum, D. A., Marchak, F., Barnes, H. J., Vaughan, J., Slotta, J., and Jorgensen, M. Constraints for action selection: overhand versus underhand grips. In *Attention and Performance XIII*, M. Jannerod, Ed. Erlbaum, Hillsdale, NJ, 1990, 321–342.
20. Rosenbaum, D. A., van Heugten, C. M., and Caldwell, G. E. From cognition to biomechanics and back: The end-state comfort effect and the middle-is-faster effect. *Acta Psychologica 94*, 1 (1996), 59–85.
21. Rosenbaum, D. A., Vaughan, J., Barnes, H. J., and Jorgensen, M. J. Time course of movement planning: Selection of handgrips for object manipulation. *Journal of Experimental Psychology: Learning, Memory, and Cognition 18*, 5 (1992), 1058–1073.
22. Santello, M. Kinematic synergies for the control of hand shape. *Archives Iteliennes de Biologie 140* (2002), 221–228.
23. Short, M. W., and Cauraugh, J. H. Precision hypothesis and the end-state comfort effect. *Acta Psychologica 100*, 3 (1999), 243–252.
24. Tuddenham, P., Kirk, D., and Izadi, S. Graspables revisited: multi-touch vs. tangible input for tabletop displays in acquisition and manipulation tasks. In *Proc. CHI '10*, ACM (2010), 2223–2232.
25. Vogel, D., and Casiez, G. Hand occlusion on a multi-touch tabletop. In *Proc. CHI '12*, ACM (2012), 2307–2316.
26. Wagner, J., Huot, S., and Mackay, W. Bitouch and bipad: designing bimanual interaction for hand-held tablets. In *Proc. CHI '12*, ACM (2012), 2317–2326.
27. Wobbrock, J. O., Morris, M. R., and Wilson, A. D. User-defined gestures for surface computing. In *Proc. CHI '09*, ACM (2009), 1083–1092.
28. Wu, M., and Balakrishnan, R. Multi-finger and whole hand gestural interaction techniques for multi-user tabletop displays. In *Proc. UIST '03*, ACM (2003), 193–202.