An Evaluation of State Switching Methods for Indirect Touch Systems

Simon Voelker, Chat Wacharamanotham, Jan Borchers
RWTH Aachen University
52056 Aachen, Germany
{voelker, chat, borchers}@cs.rwth-aachen.de

ABSTRACT

Indirect touch systems combine a horizontal touch input surface with a vertical display for output. While this division is ergonomically superior to simple direct-touch displays for many tasks, users are no longer looking at their hands when touching. This requires the system to support an intermediate Tracking state that lets users aim at objects without triggering a selection, similar to the hover state in mouse-based UIs. We present an empirical analysis of several interaction techniques for indirect touch systems to switch to this intermediate state, and derive design recommendations for incorporating it into such systems.

Author Keywords

indirect touch; three-state model

ACM Classification Keywords

H.5.2 Information Interfaces and Presentation: User Interfaces - Ergonomics, Theory and methods

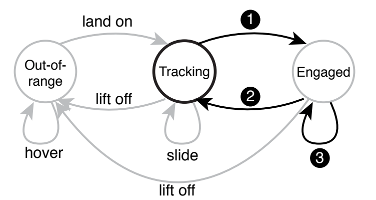
General Terms

Human Factors, Design, Measurements

INTRODUCTION

Mouse-based UIs distinguish three different input states that the system can react to: Out-of-Range (user's hand not on the device), Tracking (user moving the mouse), and Engaged or Dragging (mouse button is pressed, manipulating the object below the cursor) [3].

Some direct touch systems such as multi-touch screens support richer interactions than the mouse by using multiple fingers and hands, but they mostly lack a Tracking state. Users move from Out Of Range (a finger not touching the surface) directly to Engaged (a finger touching the surface and thus manipulating the objects beneath it). For direct touch systems, this loss is sometimes problematic since it hampers UI techniques such as tooltips, but it is not necessary since users



Method	1	2	3
Tapping	one tap	one tap	slide
Hold	hold	–	slide
PS	pressure down-up	pressure down-up	slide
PQ	pressure down	pressure up	slide + pressure

Figure 1. (Top) State transition model for three-state interaction on the indirect touch system [3]. (Bottom) Four methods of state switching.

can visually align their finger to the target before touching and thus engaging — the biggest advantage of the Tracking state.

For indirect touch systems, losing the Tracking state is crucial, since users are usually required to look at the vertical output display and not at their hands on the horizontal input surface while interacting. However, indirect touch systems have many, mostly ergonomic, advantages over horizontal direct touch systems: The users can see the vertical output form a comfortable sitting position without having to lean over a horizontal display [19], which reduces neck muscle strain and neck pain [8, 25]. Furthermore, operating with the hands on a horizontal surface is much less exhausting and faster than on a vertical touchscreen [2, 17]. Traditional desktop computers use the same device arrangement.

The aim of this paper, is to empirically evaluate four different interaction techniques that allow users to enter and leave an intermediate Tracking state on indirect touch systems. After identifying four representative techniques from a review of existing literature, we report results from testing these four techniques in three experiments covering single-touch, multiple-touch, and bi-manual interactions. We conclude with design recommendations for interaction techniques that support a Tracking state in indirect touch systems.

RELATED WORK

Indirect touch

For standard pointing tasks with a stylus, indirect input performed very similar to direct input, in terms of target acquisition and error rates. However, indirect input benefits from less occlusion for difficult targets [7]. While direct touch was faster, indirect touch had a lower error rate and was more precise for 2D/3D rotation, scale, and translation [13].

In a mixed direct and indirect touch environment, indirect input can be used as a high-precision mode because it reduces content occlusion and allows the user to interact with faraway objects in the space near the body [14, 1, 20].

Schmidt et al. [25] showed that the mapping between horizontal and vertical screen for indirect multi-touch input can be easily understood by the users. However, in their study, direct multi-touch input outperformed the indirect multi-touch input for simple aiming and dragging task in terms of task completion times. They also explained that a possible reason for this result could be that the users had to physically hover with their hand above the surface for the Tracking state, which was reported as uncomfortable by the users. This suggests introducing a switching method that allows users to rest their hands while being in the Tracking state and easily change to the Engaged state. The studies in this paper compare four different candidates for such a switching method.

Three-state input in multi-touch systems

While the Tracking state is necessary for indirect touch input, other projects introduced the Tacking state to direct touch input because of benefits of preventing errors or increasing the richness of the input [3]. Therefore, the state switching methods from direct touch systems could inform the design of those in indirect touch systems.

Pressure-based methods

In Pressure-based methods, every lightweight touch is recognized as an input in the Tracking state; the system switches to the Engaged state only when the pressure is increased [4]. Due to friction between the finger and the surface, retaining the pressure while moving the touch on the surface could be uncomfortable. Forlines et al. [8] used the light touches to preview a sequence of actions, and pressured touch to confirm the action.

Gestures

Surface gesturing, e.g., lifting the finger while it is positioned over the target (take-off) [23] or rubbing the target [21] are alternatives. In comparative studies, pressure technique and rubbing outperforms take-off. Multiple finger gestures [18] or a bimanual gesture [21] could also be used for state switching.

While the above-mentioned methods allow single-touch direct-input state switching, there is no comparison of the methods for multi-touch systems. We will now identify design criteria for state switching methods for multi-touch indirect-input systems. These criteria lead to a selection of four representative methods which were tested empirically.

DESIGN CONSIDERATIONS

In our opinion, good state switching methods should meet these properties:

Applicable to individual fingers: Methods that meet this property (1) retain the expressiveness of multi-touch input because all fingers can be used independently, (2) are widely applicable without the need to identify different digits of the hand, and (3) are extendable for multiple-user setups.

Hard to unintentionally switch states: Methods should minimize *slip-ins*, where the user unintentionally switches into the Engaged state from the Tracking state, and *slip-outs*, where the user unintentionally switches out of the Engaged state either into the Tracking or into the Out-of-Range state.

Ergonomic: Methods should allow the user to switch to or to maintain a state for an extended period of time with minimal discomfort.

In the next section, we describe four switching methods that satisfy these design considerations.

STATE SWITCHING METHODS FOR TOUCH INPUT

According to Wang and Ren [26], the fingers have four types of input properties: position, motion, physical, and event properties . On interactive surfaces, position and motion are already occupied for spatial input; therefore, only physical and event properties are left for state switching.

In this paper, we chose *pressure quasimode*, *pressure switch*, *lift-and-tap*, and *hold* as representative methods for state switching. Pressure quasimode spans the dimension of Wang's physical properties because the size, shape, and pressure of the contact area are tightly coupled. Orientation of the finger is not practical for multiple-finger usage because users have to rotate their whole hand to change the orientation. Among event properties, lift-and-tap was chosen over flicking because lift-and-tap provides a stable contact point with the surface after switching into the Engaged state. Pressure switch and hold exploit the time dimension of the physical and event properties, respectively.

An overview of these state switching methods is shown in Figure 1. Only the transitions into and out of the Engaged state differ between the switching methods.

None of these switching methods are new. Pressure quasimode and lift-and-tap have been investigated in [4]. Pressure switch is a minor adaptation of pressure quasimode to overcome the friction problem. Hold is prevalent among commercially available touch systems. However, we looked at these methods in terms of their use with multi-touch input involving multiple fingers and/or hands.

In the remainder of this section, we describe the interaction design, potentials, and limitations of each method. To determine appropriate system specific thresholds for each method, we conducted a preliminary study with five participants for each method.

Common concerns for pressure methods

Pressure Proxy

For both pressure methods, we use the length of the semi-major axis of the touch ellipse as a proxy representing contact pressure. This is supported by the direct relationship between pressure and contact radius of the human finger to a flat surface [22]. The SimPress system used contact area to represent pressure [1]. Since the contact region is always near-elliptical

[5], it is plausible to use an ellipse around the finger tip to represent the pressure. We apply a low-pass filter to the length of the major axis to eliminate jitter.

One-bit Pressure
Although previous work shows that humans can discriminate up to seven levels of pressure with visual feedback [6, 24], a realistic multi-finger switching method would have to be practical with up to 10 fingers. Therefore, for state switching, we chose a one-bit discrete pressure level instead of three bits (seven states) to reduce the mental load and physical effort in maintaining states of all fingers.

Pressure Thresholding by Rate of Change
We used rates of pressure change in thresholding to accomodate the difference among users in their ability to exert pressure. This difference is due to finger size and ability to exert force through hand and finger joints.

Pressure quasimode (PQ)

Interaction design
State switching with pressure quasimode is shown in Figure 2a. To switch into the Engaged state, the user (1) increases pressure faster than a threshold defined by the rate of pressure change $\frac{dP}{dT} > \delta_{engage}$, (2) the centroid of the contact area must still be within a radius r_{max}, and (3) the time of pressure change must not exceed a threshold t_{max}. To switch out of the Engaged state, the user can either release the pressure faster than $\delta_{disengage}$, or reduce it to less than a minimum pressure threshold, P_{min}. The rate thresholds, δ_{engage} and $\delta_{disengage}$ were used to prevent false positive recognition, e.g., the reduction of the pressure while the finger is sliding in the Engaged state. When the users increase the pressure of a finger, the centroid of the contact area drifts towards the palm of the user, the maximum drifting radius r_{max} and the time threshold t_{max} were used to distinguish pressure application from just sliding the finger in the Tracking state. In the implementation, t_{max} was also used as the time to cache touch events for processing. This time frame enables a responsive output of the state switching recognizer.

We found suitable thresholds by letting participants imagine sliding an object on the surface between two designated points on the screen. We processed the data for inflection points (as the first ascent and the last descent) and the peak of pressure.

Potentials and limitations
The benefit of pressure quasimode is that the user is continuously aware of the state of the finger is in because of haptic feedback and proprioception of the fingertip. However, holding pressure with one's finger can become tiring. Since the finger muscles cannot generate enough force, the finger has to receive extra force coming from the forearm muscles. When used repetitively, friction among tendons could cause injuries with this method [17].

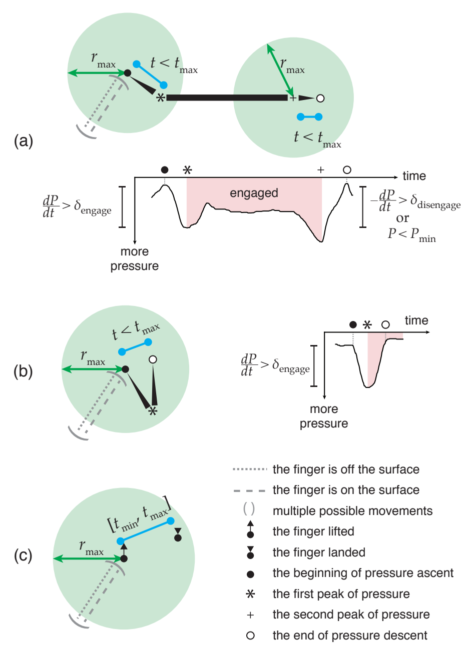
Pressure switch (PS)

Interaction design
The pressure switch method is a combination of pressure quasimode and lift-and-tap to overcome the friction problem. The user *toggles* between the Tracking state and the Engaged state by applying a short period of pressure on the screen as shown in Figure 2b. The δ_{engage} of pressure switch were the same as for pressure quasimode.

Potentials and limitations
While the friction problem is alleviated in pressure switch, the feeling of continued pressing during the Engaged state was also taken out. If the user rests the finger on the surface after engaging using momentary pressure, she may not remember that the finger is already in that state.

Lift-and-tap (Tap)

Interaction design
Lift-and-tap [16] involves a sequence of temporary lifting off from the screen and landing back on the screen, as seen in Figure 2c. A user taps once to switch into the Engaged state. The system should use the centroid of the last point before the finger lift-off to determine which control to activate, because a drifting may have occurred at the landing. Once in the Engaged state, the finger remains Engaged until the user lifts the finger out of range. Recognizing lift-and-tap in multi-touch environments must take the drifting of the centroid of the contact point and the time between lifting and landing into consideration. The threshold for the maximum distance of the drifting centroid (r_{max}) and the threshold for maximum time



(d)

Threshold	Tap	Hold	PQ & PS
t_{min} (s)	0.09		
t_{max} (s)	1.18	0.50	0.70
r_{max} (mm)	4.14	1.94	7.07
δ_{engage} (mm)			1.30
$\delta_{disengage}$ (mm)			1.14
P_{min} (mm)			0.55

Figure 2. State switching interactions details for (a) pressure quasimode, (b) pressure switch, and (c) lift-and-tap. (d) Threshold values

(t_{max}) allow discriminating tapping from repositioning the finger without any intention to switch into the Engaged state. We determined these thresholds by recording participants tapping on 12 targets spaced evenly across the screen.

Potentials and limitations
Lift-and-tap has the benefit of familiarity since it is widely used in commercially available trackpads. Nevertheless, tapping might not be usable with multiple fingers simultaneously because of the dependencies among fingers in flexion-extension movements [11]. In particular, the middle and the ring finger can move less freely of other fingers, and can stay less still while another finger moves [11].

Hold
Interaction design
Switching into the Engaged state with the hold technique is done by resting the finger on the surface such that the centroid is static within a maximum allowed radius for a certain duration. After the duration, the cursor stays in the Engaged state until the finger is lifted off the surface. There is no direct transition back to the Tracking state. The hold duration (t_{max}) in commercially available touch systems is between 0.5–1 second[1]. We asked participants to hold the finger on the target on the touchscreen and recorded the position of the centroid for 0.5 seconds to determine the maximum distance (r_{max}) that the touch centroid may drift.

Potentials and limitations
Notable limitation of hold is that switching errors may occur easily. While the user is trying to engage one finger, she might engage other fingers resting on the surface as well. To prevent this accidental activation, the user has to either lift or move other fingers; this makes the ergonomical benefit of hold questionable (see: Experiment 2). With this limitation in mind, the hold method may still be suitable for several quasi-mode widgets that require the user to remain Engaged to operate (see: Experiment 3).

EVALUATION OF STATE SWITCHING METHODS
We evaluated the switching errors of the state switching methods in three use cases: single finger, multiple fingers, and bi-manual interaction. For our experiments we adapted the Drag and Drop tasks from [9] because they encompassed Tracking, Engaging, dragging, and disengaging. For the third experiment, we used a task that represents an asymmetric bi-manual interaction.

Our three research questions were:

- Do switching methods differ in switching errors made, subjective perception, and user preference?
- Are these differences consistent over the three use cases?
- Ultimately, which switching method should be recommended for indirect touch systems?

[1] iOS 5.1: 0.5 s. Android 4.1: 0.5–1 s.

Apparatus
Participants sat at a desk with two displays as shown in Figure 3. As a the horizontal touch surface we used a capacitive touch-sensing 27″ Perceptive Pixel display is embedded in a custom-made desk surface. The horizontal display was blank.

The vertical display was used for visual output. The bottom-most pixel of this display was 13 cm above the desk surface. The surface of the display was 47 cm from the topmost touch sensing area used in the horizontal touchscreen. Both displays had the same display area and resolution: 597 × 336 mm, 2560 × 1440 pixels. This gave us a 1:1 input:output space size ratio. Both displays were connected to a Mac Pro running the software for the experiments. The effective touch frame rate of our setup was 205 Hz.

For each contact point, a circle cursor with constant diameter of 7 mm (30 px) was visualized with an absolute mapping of the centroid of the contact area to the center of the cursor in 1:1 ratio without any pointer acceleration. The cursors were outlined in the Tracking state and were filled in the Engaged state. We used a 1:1 ratio to avoid precision problems, which occur when the input surface is smaller than the output surface. Furthermore, we used an absolute mapping to prevent confusion when multiple cursors are present on the screen. Especially in multi-touch and bi-manual multi-touch input, cognitive load from mapping multiple touches and multiple cursors would be overwhelming.

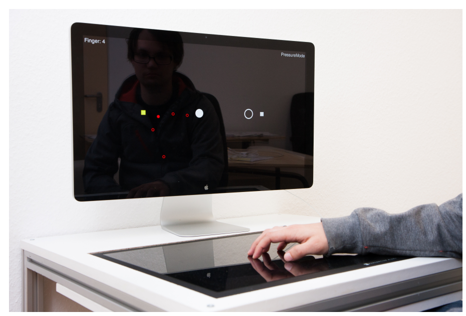


Figure 3. The experiment setup. Participants indirectly controlled cursors on the vertical screen by touching the horizontal screen.

Data Analysis
We used Generalized Estimating Equations (GEE)[2] for main analysis of error counts and Wilcoxon signed rank tests with Bonferroni correction for post-hoc (pairwise) comparisons. For the trial time (Experiment 1), a repeated-measure ANOVA and paired t-tests were used.[3]

Note that the error rates reported in the following experiments were calculated as per trial averages. Although the differences may seem small (e.g., 0.1 errors), when projected to the real use—over a longer period and more frequent switching—these small differences are practically significant.

EXPERIMENT 1: SINGLE FINGER

[2] GEE details: Poisson distribution, log link function, and an independent covariance structure.
[3] Statistically significant for all main analyses at $\alpha = .05$ and for all post-hoc tests at $\alpha = .0083$ $(= .05/6)$

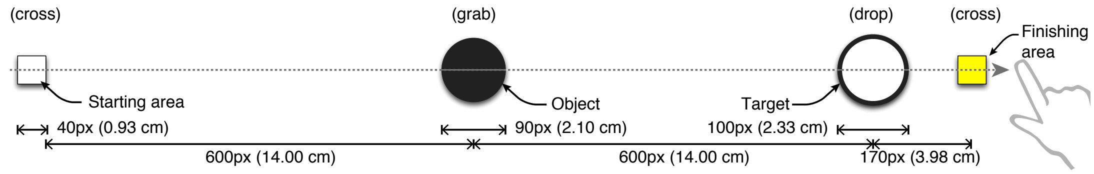


Figure 4. A configuration of the single-finger task. The participant tracks the cursor across the entry, grabs the object, drops the object at the target, and crosses the exit.

In this experiment, we investigated the effect of different switching methods using a single finger, which is the simplest way to interact with a multi-touch screen.

Although a previous investigation of indirect touch object manipulation [20] used only the thumb, the index, and the middle finger, we decided to include all ten fingers in this experiment for three reasons. (1) The ring and the little finger are used to switch states in other input devices, e.g., using the little finger to hold down shift while typing. (2) We did not find any proof in the literature that warrants exclusion of any fingers in the interaction with interactive surfaces.

We counterbalanced the order of fingers and pilot tested the procedure to prevent fatigue effect.

Task

The screen, shown in Figure 4, contained a starting area (left blank square), the object (filled circle), the target (blank circle), and a finishing area (right filled square).

For each of the four techniques, the participants had to execute the following sequence of actions: The participant was first told by the experimenter which finger to use. To start the trial, she had to track the cursor crossing the starting area, and then onto the object, which turned yellow when the cursor was in grabbing range. Here, she had to invoke the switching technique to switch into the Engaged state to grab the object. The participant had to drag the object to the target; the cursor had to remain in the Engaged state until it reached the target. If the object was dropped, she had to re-grab it and resume the task. When the object was in range of the target, the target turned yellow. There, the participant had to switch the state of the cursor to drop the object onto the target. If she accidentally re-grabbed the object after dropping it onto the target, she had to drop it onto the target again. The trial ended after the participant tracked the cursor into the finishing area.

To minimize the time the user took to aim at the targets, which might have confounded the state switching behavior, we used the following specifications: (1) The object and the target were large: 2.1 cm (90 px) and 2.33 cm (100 px) diameter respectively and as such were easy to aim at with a cursor of 7 mm (30 px) diameter. (2) The color of the object and the target changed when the cursor was within range for grabbing or placing the object. (3) The drop was successful when the object was released close to the target within a distance < 1 cm.

Measurements

The recorded raw touch data included timestamps, coordinates, the length of the major and minor axes of the touch ellipse, and its rotation angle. We recorded the cursor position, the object state, and its position at the same frame rate. We distinguished three types of *Switching errors*:

- *Tracking slip-ins (TSI)*: Errors triggered by slipping into Engaged state between starting point and the object.
- *Dragging slip-outs (DSO)*: Errors triggered by slipping out of the Engaged state while dragging the object towards the target. This caused the finger to lose the focus of the object; the participant had to re-grab the object.
- *Placement slip-ins (PSI)*: Errors triggered by slipping into the Engaged state after the object was dropped onto the target. This caused the object to be re-grabbed, and the participant needed to drop the object onto the target again.

Experimental Design and Procedure

We conducted the experiment with 8 Computer Science students aged 24–34. They were volunteers from our campus; no monetary compensation was provided. All were right-handed males. Each participant had to conduct four trials with different movement directions (up, down, left, right) for all 10 fingers for each switching technique. This resulted in a total 1280 trials over all users.

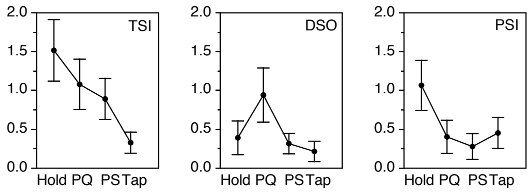
The order of switching methods was counterbalanced using a Latin square. The directions and order of the fingers were randomized for each user. After two methods, participants took a five minute break. On average, the experiment took 30 minutes per participant.

During the task, we asked the participants to place all fingers on the screen; this reflected the ergonomical use of an indirect touch setup as we envisioned it. Therefore, multiple cursors were shown. Participants were instructed to avoid using cursors other than the one associated with the finger in use to interact with the object. Each cursor was tracked individually. Only data from the cursor that grabbed the object was used in the analysis. The influence of multiple fingers was investigated in Experiment 2.

At the end of each switching method, we asked the participants to comment on their perception of speed and accuracy of the method and any fatigue of their hand and arm. We asked then to choose the most favorable method.

Result

GEE showed a statistically significant effect of techniques on TSI Wald $\chi^2_{3,N=320} = 32.92$, $p < .001$, on DSO Wald $\chi^2_{3,N=320} = 14.96$, $p < .001$, and on PSI Wald $\chi^2_{3,N=320} = 41.033$, $p < .001$. The detailed result and the post-hoc analysis are shown in Figures 5 and 6. A repeated measures ANOVA shows significant effect of method, $F(3, 957) = 3.69, p = .0117$. The details are shown in Figure 7.

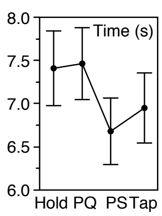


	TSI	DSO	PSI
Hold	1.51 [1.12, 1.91]	0.39 [0.17, 0.60]	1.06 [0.74, 1.38]
PQ	1.08 [0.75, 1.40]	0.94 [0.59, 1.29]	0.40 [0.19, 0.61]
PS	0.89 [0.62, 1.15]	0.31 [0.18, 0.44]	0.28 [0.11, 0.44]
Tap	0.33 [0.19, 0.46]	0.21 [0.08, 0.34]	0.45 [0.25, 0.65]

Figure 5. Error count per trial from Experiment 1 (Mean & 95% CI)

	TSI		DSO		PSI	
PQ – Hold	−194	.0920	−245.5	<.001	−330	<.001
PS – Hold	−316.5	.0057	−14	.820	−313.5	<.001
PS – PQ	−129.5	.2060	−274	<.001	−19.5	.571
Tap – Hold	−474.5	<.001	−60.5	.107	−335.5	<.001
Tap – PQ	−340	<.001	−281.5	<.001	18.00	.626
Tap – PS	−201	<.001	−58.5	.200	63.50	.181

Figure 6. W statistics and p values of the post-hoc analysis of error counts in Experiment 1. Statistically significant differences are highlighted.



	Trial time (s)
Hold	7.40 [6.97, 7.84]
PQ	7.46 [7.04, 7.87]
PS	6.67 [6.29, 7.06]
Tap	6.94 [6.54, 7.35]

	t_{319}	p
PQ – Hold	0.18	.8542
PS – Hold	−2.64	.0087
PS – PQ	−2.83	.0050
Tap – Hold	−1.67	.0968
Tap – PQ	−1.98	.0487
Tap – PS	0.97	.3311

Figure 7. Experiment 1 trial time (Mean & 95% CI) and post-hoc result.

Participants described that lift-and-tap was natural and intuitive: *"I would use this if there were no instructions"* and *"It's the closest to the mouse."*. In contrast, participants felt that the hold method was unfamiliar, mostly because of slip-ins: *"Hold is the most irritating. You get stuck somewhere all the time."* and *"False activations are annoying, it's prevented me [from moving] faster."*. Participants mentioned tiredness while using the pressure quasimode method: *"This cramps my hands up more than the others."* and *"For long distances the friction could be a problem."*. Four participants chose lift-and-tap as the most favored method, followed by hold (3), and pressure quasimode (1).

Discussion

While Hold yielded a high error rate (TSI & PSI), it was favored by 40% of the participants. We speculate two reasons for this contradiction: (1) During dragging (DSO), hold performed no worse than other methods. With dragging as the main goal, the user may have perceived this technique as better than it was. (2) Inadvertent engaging (TSI) caused no problems here because the screen only contained the target object. In reality, with many onscreen objects, TSI errors would potentially engage unwanted objects.

Although pressure switch, pressure quasimode, and lift-and-tap require users to explicitly switch to the Engaged state, lift-and-tap had lower TSI than the others. While this may have been the result from the lack of familiarity with pressure-based methods, further studies with more repetitions are needed to be conclusive.

The result from pressure quasimode confirms that it is difficult to maintain pressure while dragging across the screen—three times more DSO errors occurred than with lift-and-tap. The participants' comments also supported this.

As expected, the methods with more errors yielded longer trial times. The long time of hold correlates with a high rate of TSI and PSI errors, while the that of pressure quasimode correlates with high TSI and DSO. Although the lower times for lift-and-tap were not statistically significant, we surmise that this effect would be more apparent in real use, in which more errors would require more corrections.

In summary, we recommend the lift-and-tap method for single finger due to its low error rate across the board and the favorable qualitative feedback.

EXPERIMENT 2: MULTIPLE FINGERS

When multiple fingers are used, the fingers may interfere with each other. In the second experiment, we investigated how the performance of switching methods differed when using multiple fingers of one hand.

Task

The task, shown in Figure 8, extends the task from experiment 1 to multiple objects and targets. The participants were instructed to track two cursors crossing both starting areas (shown in the figure as the blank square on the left). Then, the participants had to drag the fingers towards the first object, grab it, drag the cursors towards the second object, and grab it. The participants had to keep both objects Engaged until they were located over their respective targets. Then, they had to move to the finishing areas behind the targets. The distance between both objects and both targets was large enough (10.2 cm; 440 px) to insure that both objects could not be grabbed or released at the same time. The distance between the center of each object to the center of the respective target was constant at 18.6 cm (800px).

To limit the number of trials to be feasible in one experiment session, only the thumb, the index finger, and the middle finger of the dominant hand were tested. The object closest to the user had to be grabbed using the thumb or the index finger with depending the condition. This is the movement that allows the hand to naturally stay in line with the arm.

Measurements

The errors in this experiment may occur in three phases: during object acquisition, during dragging with both fingers,

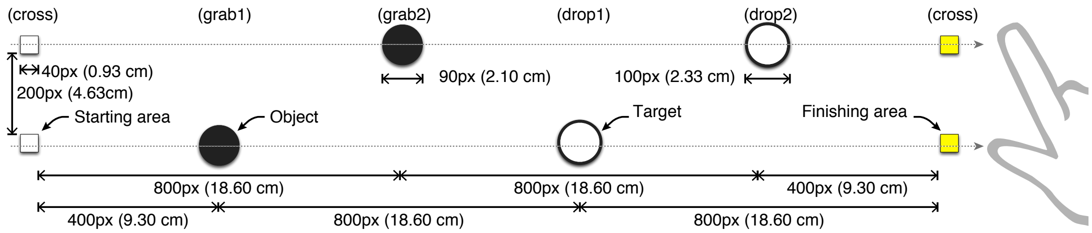


Figure 8. A configuration of multiple-finger task. The participant acquired two objects in order before dropping each of them in their respective targets.

and during object placement onto the targets. In these three phases, errors may occur with the first or the second finger. Therefore, besides *overall errors*, we classified errors into six classes:

- *Acquisition slip-ins (ASI):* The number of errors occured in the second finger while the first finger is acquiring the first object.
- *Acquisition slip-outs (ASO):* The number of errors occured in the first finger while the second finger is trying to acquire the second object.
- *Placement slip-ins (PSI):* The number of errors occured in the second finger while the first finger is trying to place the first object in the target.
- *Placement slip-outs (PSO):* The number of errors occured in the first finger while the second finger is trying to place the second object in the target.
- *Dragging slip-outs in the first finger (DSO1):* The number of errors occured in the first finger during dragging. The participants had to retain all objects for at least 9.3cm (400px).
- *Dragging slip-outs in the second finger (DSO2):* The number of errors occured in the second finger during dragging.

The classification of these errors allows us to pinpoint where the errors occur and to investigate the potential of using different methods for the first and the second finger. Since an error requires the participant to re-grab the object which may cause subsequent errors, only the first error was counted.

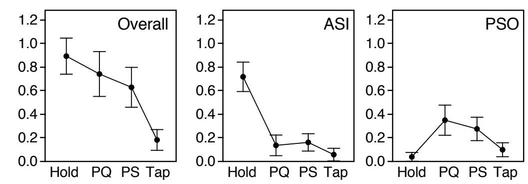
Experimental Design

We conducted the experiment with 8 computer science students (age 24–28; one female; all of them right-handed). Each of the participants had to perform two trials in different directions (from left to right, from right to left) for six combinations of fingers (576 trials in total).

The order of switching methods were counterbalanced among participants, while the order of the finger combinations and the direction was randomized. The experiment took 35 minutes on average. We asked for qualitative feedback in the same manner as in Experiment 1.

Result

GEE shows a statistically significant effect of methods on overall errors Wald $\chi^2_{3,N=384} = 58.05$, $p < .001$. The interaction effect of finger order on overall errors was not significant Wald $\chi^2_{5,N=384} = 5.16$, $p = .397$. In break down errors, a significant effect of methods was found only on ASI, Wald $\chi^2_{3,N=384} = 93.24$, $p < .001$, and on PSO, Wald $\chi^2_{3,N=384} = 26.05$, $p < .001$. ASO, DSO1, DSO2, and PSI occured in very small numbers and their effects were not statistically significant. The detailed results and post-hoc analyse are shown in Figure 9 and 10.



	Overall	ASI	PSO
Hold	0.89 [0.74, 1.04]	0.71 [0.59, 0.84]	0.03 [0.00, 0.07]
PQ	0.74 [0.55, 0.93]	0.13 [0.04, 0.22]	0.35 [0.22, 0.47]
PS	0.63 [0.46, 0.79]	0.16 [0.08, 0.23]	0.27 [0.17, 0.37]
Tap	0.18 [0.09, 0.27]	0.05 [0.00, 0.11]	0.09 [0.03, 0.15]

Figure 9. Error count per trial from Experiment 2 (Mean & 95% CI)

	Overall		ASI		PSO	
PQ – Hold	−132.00	.2929	−692.50	<.001	192.50	<.001
PS – Hold	−298.00	.0071	−645.00	<.001	116.00	<.001
PS – PQ	−186.50	1.811	19.00	.5262	−77.00	.2143
Tap – Hold	−816.00	<.001	−831.00	<.001	13.00	.3877
Tap – PQ	−604.50	<.001	−14.00	.2676	−206.50	<.001
Tap – PS	−335.50	<.001	−42.50	.0405	−136.00	.0025

Figure 10. W statistics and p value of post-hoc analysis of error counts in Experiment 2. Statistically significant differences are highlighted.

Comments from the participants also indicate a problem with Hold, especially related to slip-ins, *"[Hold] is hard, [I] cannot stop one finger from activating."* and *"You are always pressing something that you don't want."*. Drawbacks of pressure quasimode were also noted by participants: *"[pressure quasimode is] hard to control just one finger"* and *"It's hard to press just the one you want"*. Lift-and-tap was favored by seven participants, follwed by pressure switch (3), and hold (2). None of the participants preferred pressure quasimode. The reason were that lift-and-tap was *"faster"*, *"easier"*, and *"predictable"*.

Discussion

Again, lift-and-tap significantly outperformed the other methods in terms of overall errors. Pressure switch had fewer errors than hold. As seen from the ASI, a lot of slip-in error of the second finger occurred while the participants tried to acquire the first object, which contributes to the high error in hold comparing with other methods. The slip-ins of the first finger when dropping the objects (PSO) occurred more frequently in pressure switch and pressure quasimode than in the other conditions.

Since lift-and-tap had a relatively lower error rate and was more preferred than the other three methods, we recommend tapping as the first choice for multiple-finger uni-manual interaction, especially if the interaction involves frequent state switches.

EXPERIMENT 3: BI-MANUAL

In the last experiment the participants had to to do a asymmetric bi-manual tasks. An example of such a task in conventional desktop computer interfaces is when one hand is using the mouse to manipulate an object on the screen while the other hand presses the keyboard to issue commands. Asymmetric bi-manual tasks are precivied as more complex than uni-manual or symmetric bi-manual tasks [10, 15]. We hypothesize that (1) state switching in one hand influences the state switching in the other hand, and that (2) different state switching methods influence switching errors and switching time differently.

Task

This task was designed to represent translation, scaling, and rotation manipulations on a touch systems. With the dominant hand, the participants had to drag two objects with the thumb and the index finger through a maze. The two objects were two circles with a width of 1.8 cm (80px). The walls of the maze were displayed as 1 cm thick white lines. To move the objects through the maze, the participants had to drag through 8 pairs of gates, which where placed at specific points on the walls. The width of each gate was 2.4 cm (100px), and the distance between the two gates varied between 0 cm and 3.98 cm (170px) to force the participant to pinch the fingers to drag the objects through the gates. The gates were displayed as either blue, red, or yellow areas on the walls, as shown in Figure 11. Each gate differed in gap size, requiring the user to translate each circle individually.

If a dragged object was blocked by a wall the finger could slide off the object. In this case, the object had to be reacquired.

The gates could be opened by holding a correspondingly colored button located at the lower edge of the table on the non-dominant side. Thus, the participants needed to chord single or multiple keys with the non-dominant hand while using the dominant hand to move the objects through the opened gates. To indicate which object should be dragged through which gate, the gates were drawn in the corresponding color of the object.

After the participants had moved both objects through a pair of gates the colored buttons were disabled to enforce an engaging of the hand to open the next pair of gates. A trial was complete when both objects passed the last pair of gates.

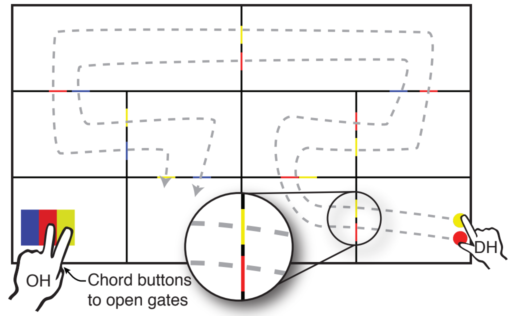


Figure 11. Bi-manual interaction task. The dominant hand (DH) moves a pair of circles through the colored gates while the opposite hand (OH) chords the buttons to open gates of the corresponding colors.

Measurements

In this task, we focus on situations where the user interacts with both hands, specifically, when the objects are within a distance of 1.6 cm (80px) of a gate opening. During this period, the user must move both objects using the fingers of the dominant hand while simultaneously keeping the buttons pressed with the fingers of the non-dominant hand. We measured three types of error:

- *Dominant hand slip-outs (SO_{DH}):* The number of times the dominant hand slips out during bi-manual interaction.
- *Opposite hand slip-outs (SO_{OH}):* The number of times the non-dominant hand slips out during bi-manual interaction.
- *Overall errors:* Sum of both slip-outs.

Methods with low overall errors are preferred. Methods with low $\mathrm{SO_{DH}}$ cause fewer error in the main task (object movement) and should be recommended for dominant hand input. Methods with low $\mathrm{SO_{OH}}$ cause fewer error in the secondary task (buttons holding) and should be recommended for non-dominant hand input.

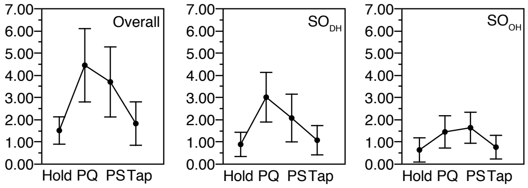
Experimental design

We conducted the experiment with 8 computer science students (age 24 to 30; 2 female; all of them right-handed). Each participant conducted two trials in different directions for each switching method, resulting in a total of 64 trials. The order of switching methods and blocks was counterbalanced across participants, while the order of direction was randomized for each user. The experiment took 15 minutes on average. We collected qualitative feedback in the same manner as in Experiment 1.

Result

GEE shows a statitistically significant main effect of switching methods on overall errors, Wald $\chi^2_{3,N=64} = 126.17$, $p < .001$, on non-dominant hand slip-out ($\mathrm{SO_{OH}}$), Wald $\chi^2_{3,N=64} = 25.16$, $p < .001$, and on dominant hand slip-out ($\mathrm{SO_{DH}}$), Wald $\chi^2_{3,N=64} = 23.07$, $p < .001$. The detailed results and post-hoc analysis are shown in Figures 12 and 13.

Participants favored lift-and-tap because it was easy and did not require the user to maintain force: *"You don't waste time and it's easier to apply"*, *"Sometimes I didn't even have to*



	Overall	SO$_{DH}$	SO$_{OH}$
Hold	1.50 [0.88, 2.12]	0.88 [0.33, 1.42]	0.63 [0.08, 1.17]
PQ	4.44 [2.79, 6.09]	3.00 [1.88, 4.12]	1.44 [0.71, 2.16]
PS	3.69 [2.11, 5.26]	2.06 [0.99, 3.14]	1.63 [0.93, 2.32]
Tap	1.81 [0.84, 2.79]	1.06 [0.40, 1.72]	0.75 [0.22, 1.28]

Figure 12. Error count per trial from Experiment 3 (Mean & 95% CI)

	Overall		SO$_{DH}$		SO$_{OH}$	
PQ – Hold	49.50	.0032	50.00	0.0070	21.50	.0713
PS – Hold	38.50	.0121	28.00	.0225	28.50	.0488
PS – PQ	–17.50	.3346	–22.50	.2074	3.50	.6250
Tap – Hold	6.00	.6240	4.50	.6719	4.50	.6133
Tap – PQ	–46.00	.0020	–42.50	.0056	–13.00	.0781
Tap – PS	–34.00	.0059	–18.50	.0625	–24.50	.0117

Figure 13. W **statistics and** p **value of post-hoc analysis of error counts in Experiment 3. Statistically significant differences are highlighted.**

look [at the non-dominant hand] to select the colors", and *"I'm not forced to press all the time"*. Participants also commented on the potential of hold for long-distance dragging and for the non-dominant hand: *"It's good that you don't have to move your left hand"* and *"You're not losing the targets on accident. You don't have to do anything with the right hand and tap the [buttons] with your left"*. For the ranking, five participants chose lift-and-tap, and three participants chose hold as their most favored method. None of the participants chose pressure switch or pressure quasimode.

Discussion

Less overall errors in lift-and-tap and hold indicate that these methods are suitable for bi-manual interaction. The lower error rate of hold was to be expected because of two reasons: First, in the dominant hand, the user can remain in the Engaged state for the whole task. As seen from the second experiment, only few errors occured while dragging with multiple fingers. Second, the user only has to maintain the finger contacts of the dominant hand with the surface while switching the state using the non-dominant hand. In contrast, it is easier to make mistakes in pressure quasimode and pressure switch because the participants had to maintain the finger pressure.

In summary, the state switching in one hand causes more errors in the opposite hand, especially in pressure quasimode and pressure switch. As switching methods influence switching errors differently, we recommend lift-and-tap and hold to be used in asymmetric bi-manual tasks.

DISCUSSION & CONCLUSION

In this paper, we identified four different switching methods that introduce a third interaction state for indirect touch systems. We conducted three experiments to compare these methods in three interaction scenarios: single finger, multiple fingers, and bi-manual interaction.

Use lift-and-tap as a default state-switching method

Across all three experiments, lift-and-tap outperforms other switching methods in terms of error rate and user preference. We believe the main reason for that is the explicit finger-up movement. It is less likely to be triggered by accident than, e.g., changing pressure or pausing a finger temporarily. This assumption is also supported by qualitative feedback. Therefore, we propose to use lift-and-tap as the switching method for indirect touch systems.

Consider the influence of task & context

While we recommend lift-and-tap as a default method, designers should also consider the influence of the form factor, the UI widgets, and the task. For example, since lift-and-tap loses the touch temporarily, two nearby touches may trade their places, especially in a small device.

The nature of the UI widget and the task should also be considered when choosing a method. For example, hold and pressure quasimode may be more suitable than lift-and-tap for an on screen quasimode modifier key. Interaction designers may allow an alternative switching method on these UI widgets in addition to lift-and-tap.

In some scenarios, a combination of lift-and-tap and hold can be beneficial in bi-manual interaction. As the third experiment showed, hold yielded almost no errors—comparable to lift-and-tap—for targets of which position is fixed, e.g., a button.

For example, in a 3D scene construction application [12], the user could use the non-dominant hand to select a virtual object while placing it on the scene with the dominant hand.

LIMITATIONS

The small number of participants, together with the conservative statistical analysis criteria, may have resulted in a lack of statistical power—some effects of the methods may not have been detected. Despite the clear superiority of lift-and-tap in our experiment, we believe that other methods, especially pressure switch and hold might be useful for some tasks or context-specific applications. Since our participants were from computer science who had experience with touch-screens, the results may not be generalizable for first-time users.

While we determined the thresholds from users' behavior, the thresholds presented were specific to our hardware. Interaction designers can use these thresholds as a starting point for their systems and adjust them according to the temporal and spatial sampling resolution of the sensor.

Of the four methods, participants might not be familiar with pressure switch and pressure quasimode. Although we let the participants familiarize them selfs with each technique, it is hard to beat their experience in lift-and-tap and hold which are ubiquitous on touch screens and track pads. We described the used thresholds and presented all results with CIs to inform future replications, meta-analyses, and design.

FUTURE WORK

In this paper, we only analyzed the methods in terms of the state switching errors. As the next step, we will also address the open question about how precise the users can select objects with each of the methods using a single finger and multiple fingers at the same time. Additional aural and visual feedback in pressure quasimode may allow users to better control the switch. An informal observation among authors indicates a strong learning curve of the switching methods. A further investigation of the performance of trained users could lead to different results. Finally, in this paper, we only used a 1:1 mapping between the input and the output area. In future studies, we also want to investigate how much this ratio can be changed in the way that the output area will be larger than the input area while maintaining nearly the same precision.

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