Comparing User Performance with Single-Finger, Whole-Hand, and Hybrid Pointing Devices

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ABSTRACT
Researchers have explored pointing devices operated by a single finger, but their advantage was not clear compared to conventional mice controlled by the whole hand. To incorporate the benefits of both, we prototyped hybrid pointing devices that combined both finger and hand movement to control the cursor, and experimentally compared their performance with single-finger and whole-hand devices. Results showed that such hybrid devices have the potential to improve pointing performance in terms of time, error, and bandwidth, especially for precise pointing.

Author Keywords
Pointing, mouse, experimental study, finger, hand, hybrid.

ACM Classification Keywords
H5.2. Information interfaces and presentation: User Interfaces.

General Terms
Design, Human Factors

INTRODUCTION
Over four decades have passed since the computer mouse was invented, and yet it still remains the prevalent desktop pointing device in terms of cost, reliability and ease-of-use. Although the form-factors and ergonomic designs of mice have evolved significantly and are increasingly diverse, the basic operation largely remains the same: the user uses the entire hand to grasp and move the whole device. As applications and usage scenarios of computers continue to also diversify, other forms of pointing devices have been developed commercially, especially those that replace the mouse movement with a single finger to control the cursor, such as touchpad, TrackPoint™, or finger-mounted mouse. Although intuitively fingers are capable of more delicate control, we are aware of research indicating that using a single finger does not necessarily lead to improved pointing performance when compared to whole-hand movement [1]. We build on this literature, by studying a new class of hybrid pointing devices for cursor control, where the combination and coordination of both hand (mouse) and finger motion is feasible for cursor control. We wish to determine whether this combination will outperform either one used in isolation. To understand this, we prototyped two such hybrid pointing devices, and experimentally compare their performance with single-finger and whole-hand pointing devices.

RELATED WORK
Target pointing tasks have been extensively investigated, and are considered to consist of one initial coarse ballistic movement and several finer corrective movements [6]. The total movement time MT is best modeled by Fitts' law [4]: $MT = a + b \log_2(A/W+1)$, where A and W are target distance and width respectively, and a and b are constants determined by the pointing device used. In particular, the reciprocal of b is referred to as Index of Performance (*IP*) or bandwidth, which measures the fundamental information capability of the device. Fitts' law has been validated in many scenarios, including with cursor acceleration [3].

Although finger-based input seems a natural way to carry out pointing tasks, the performance benefit of using the finger as a pointing device has not been confirmed. Balakrishnan and MacKenzie [1] found that the index finger alone does not perform as well as the wrist or forearm in pointing tasks in terms of *IP*, but the thumb and index fingers in coordination outperform all above cases. Their study examined each joint in isolation by mechanically constraining other joints. It is not clear how their conclusion translates to realistic scenarios where all limb movements are unconstrained and could be combined. Gokturk and Sibert investigated the pointing performance of the index finger by direct pointing and by controlling an isometric TrackPoint [5], but did not test the finger in mouse-style indirect pointing.

On the other hand, a few researchers have explored combining finger input with regular mice [2, 7], however these mainly focused on using the finger for gestural input instead of controlling the cursor. There has not been research that investigated hybrid pointing devices that combine finger and hand movements.

DEVICES
In addition to a regular mouse controlled by the whole hand, we prototyped three mouse-style pointing devices to allow us to examine the single-finger and hybrid control mechanisms.

FingerMouse
FingerMouse (Figure 1a) can be considered a miniature mouse, controlled using a single finger (usually the index finger). It consists of a round-shaped plastic plate roughly the size of a fingertip. The user places the finger on top of the plate and slides it on the desk. The movement of the finger plate maps to that of the cursor. A button inset in the finger plate triggers mouse click, which can be easily pressed or released without needing to reposition the finger.

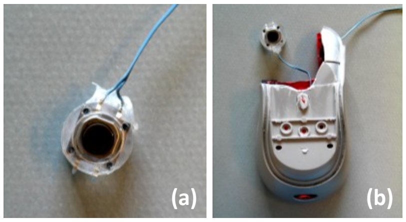

Figure 1. (a) FingerMouse.
(b) DualHybrid/FingerHybrid (right-handed version).

DualHybrid

Inspired by Villar et al.'s "articulated mouse" [7] which leveraged mechanically connected finger plates for multi-touch input, DualHybrid (Figure 1b) consists of a finger plate attached to a mouse body, and combines the movements of both to drive the cursor. We replaced the upper-left part of a regular mouse, and used a thin wire to attach a finger plate similar to that used for the FingerMouse. The user holds the device as s/he would hold a regular mouse, but resting the index finger on the movable finger plate. The cursor movement maps to the *sum* of the finger plate movement and the mouse body movement (both relative to the desk). In practice it is not possible to move the hand without also moving the finger. This means that moving the finger plate relative to the mouse body drives the cursor at half the Control-Display (CD) gain of that when moving the whole device altogether (which sums hand and finger movement in the same direction). This provides the user the ability to achieve coarser cursor control with the whole hand, and finer control with the finger. We speculate that this will improve pointing performance compared to using the finger or hand alone, especially for small targets requiring precise pointing.

FingerHybrid

FingerHybrid uses the same hardware (therefore the same grasping posture) as DualHybrid, however, the cursor movement is only mapped to that of the finger plate. This device presents an interesting case: although the input mapping is the same as FingerMouse, the fact that the user is holding the mouse body with the hand may result in thinking of moving the hand and the finger as two separate actions, a mental model more similar to that of DualHybrid. We are curious whether the actual input mapping or the mental model would prove more dominant in the user performance.

It should be noted that being a single-finger or whole-hand device does not necessarily mean it only involves one type of user movement. The user is still free to move the hand with FingerMouse, or use fingers to adjust the position of the regular mouse or the body of the hybrid devices.

To simplify implementation, these devices do not have embedded mouse sensors. Instead we simulate the motion sensing by using Microsoft Surface™, a computer-vision-based interactive table (with display turned off) as the desk, and employ the built-in connected component tracking algorithm in Surface SDK to track the positions of the finger plate and mouse body. The relative movements of the parts are then translated into cursor movement on the screen. To ensure a fair comparison, in our experiment the regular mouse was also tracked using the Surface in the same way. For clicking, the button on the devices is connected via a thin wire to external hardware, which generates mouse-click events whenever the button is pressed.

EXPERIMENT SETUP

Apparatus

The experiment was run on a 20-inch 1600x1200 monitor connected to and placed on the Surface, which was raised to allow it to be comfortably used as a desk.

Cursor acceleration is a common feature in contemporary operating systems, and was shown to improve pointing performance [3]. This was taken into account in the experiment. For each device, we supported both constant CD gain and cursor acceleration (CD gain increases as device movement speed increases). In the constant gain case, all devices had a CD gain of 1.5 (1mm device movement = 1.5mm cursor movement) when the device is moved as a whole (i.e. for DualHybrid the finger plate had a 0.75 gain when moved relative to the body). For the cursor acceleration case we used the Windows XP/Vista acceleration curve as illustrated in [3], where an extra multiplying factor (0.5 ~ 2.3) is applied to the constant CD gain value depending on the device movement speed. For DualHybrid, the acceleration factor is applied to the finger plate and the mouse body separately depending on their movement speeds (relative to the desk) respectively.

Task

A reciprocal 2D pointing task was used for all devices. For each group of trials, two circular targets of equal size appeared on the screen at locations symmetric from the center, with the orientation between them randomized. The target to be selected was highlighted in green, the other gray. Participants moved the crosshair cursor onto the target and clicked the physical button to select. The target must be successfully selected before they can proceed to the next trial. Once the target is selected, a short beep is played to indicate success and the two targets swapped colors. Participants kept selecting the next target until the group of trials finished. Participants were instructed to perform as quickly and accurately as possible. An error was counted when participants clicked outside the intended target. We measured the movement time (between two clicks) and the number of errors made in each trial.

Design

A fully crossed within-participant factorial design was used. Independent variables include target distance *A* (128, 256, 512, 1024 pixels), target width *W* (4, 8, 16, 32 pixels), *Device* (Regular Mouse, FingerMouse, FingerHybrid, DualHybrid), and cursor *Acceleration* (no, yes).

Each participant used all four devices, and for each device both with and without acceleration. The presentation order of *Device* and *Acceleration* was counterbalanced across participants. Within each condition combination, three consecutive blocks were performed. In every block, each combination of *A* and *W* was tested for one group of 2 trials, with the presentation order randomized. This resulted in a total of 768 trials per participant. Participants were asked to keep the error rate under 10% during each block (instead of the more typical 4% used for these type of experiments, given the extremely small targets we included: 4 pixels ≈

1mm). 10 practice trials were performed before each *Device-Acceleration* combination started.

16 right-handed volunteers, 13 male and 3 female, between 20~49 years old, participated. The experiment lasted between 1~1.5 hours for each participant. Participants were encouraged to take breaks between blocks.

RESULTS

Usage Patterns and Feedback

To set the context of the quantitative analysis, we first report usage patterns of the devices observed during the experiment.

As we expected, most participants did not differentiate the mental model between the two hybrid devices. With FingerHybrid they still consciously controlled the hand and the finger as separate actions although the cursor responded to the finger plate only, whereas with FingerMouse the finger was considered the sole focus of control.

Most participants used the hybrid devices in a similar pattern: start with a coarse ballistic movement of the whole device to move the cursor near the target, then stop the hand and use finger movement only to refine the cursor position. Relatively few cases of simultaneous hand and finger (relative to the hand) movement were observed. A few participants employed a slightly different strategy with FingerHybrid that is to move the finger in the same direction of the hand movement to gain extra speed in the ballistic stage when there was no cursor acceleration, but again revert to finger movement only for the final adjustment. In addition, when targets are near each other, participants tended to use finger movement only without moving the whole hand.

With FingerMouse such division of finger/hand movement was much less obvious. The hand movement was thought solely as to augment the range of the finger movement, and not planned consciously.

The Regular Mouse was controlled by the whole hand, however, this does not mean the hand remained in a rigid grip and relied purely on wrist/arm movement. On the contrary, participants were constantly using several fingers in coordination to adjust the position of the device within the hand, enabling fairly delicate movement – outperforming the mouse was not as easy as it seemed.

Participants also provided subjective feedback on the devices. DualHybrid was preferred by most for the flexibility of control granularity and feeling of accuracy. Interestingly, on first impression several users of FingerHybrid commented that having a non-functional main body seemed counter intuitive. However, once these users had a chance to try the device, the body was considered a more important feature that allowed the user to stabilize their finger pose, as well as acting as a comfortable hand rest. FingerMouse was appreciated for occupying less space (good for mobile usage) and not enforcing a particular hand posture, but the small size and light weight made it harder to stabilize, and therefore often suffered from overshooting or untended movement. Unsurprisingly, many participants still found the familiarity and mature ergonomic design of the regular mouse appealing.

One inconvenience specific to the current hybrid prototypes was that they were less easy to acquire or clutch, caused by the soft connection between the finger plate and the body. This in the future could be solved by having a rigid articulated connection as in [7], as well as potential features to retract the finger plate to the main base during clutching. However this did not have a considerable impact in our experiment, given the device only needed to be acquired once in each condition and the surface was large enough to make clutching unnecessary.

Movement Time

The overall average movement time (*MT*) was 2330 ms. Repeated measure analysis of variance showed no significant main effect for *Device* ($F_{3,45}$ = 1.47, p = .236), but a significant improvement caused by *Acceleration* ($F_{1,15}$ = 8.93, p = .009): 2386 ms without acceleration, and 2274 ms with acceleration. However, there was a significant interaction between *Device* and *Acceleration* ($F_{3,45}$ = 5.26, p = .003). This is illustrated in Figure 2.

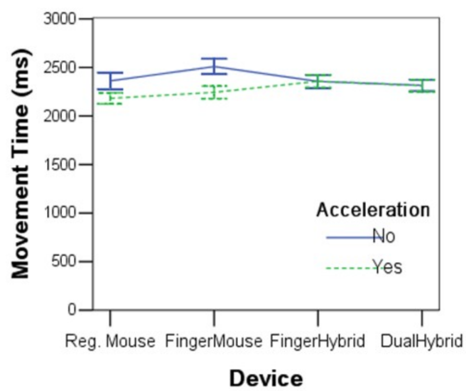

Figure 2. Movement time (std. err. bars).

Without acceleration, the simple effect of *Device* was marginally significant ($F_{3,45}$ = 2.76, p = .053): DualHybrid was fastest (2316 ms), followed by FingerHybrid (2356 ms) and Regular Mouse (2361 ms), and FingerMouse was slowest (2509 ms). In particular, this *MT* difference was most notable with smaller *W* (4 and 8 pixels). This confirmed our speculation that the dual control granularities offered by DualHybrid improved pointing performance especially for smaller targets. Conversely, consistent with the findings in [1], the reliance on a single finger compromised the performance of FingerMouse, whereas both FingerHybrid and Regular Mouse leveraged some coordination between fingers/hand, as found in the usage patterns.

With acceleration, the simple effect of *Device* was significant ($F_{3,45}$ = 2.93, p = .044), showing a different trend: Regular Mouse was fastest (2182 ms), followed by FingerMouse (2244 ms), DualHybrid (2312 ms), and lastly FingerHybrid (2358 ms). Interestingly, acceleration improved average *MT* for both FingerMouse and Regular Mouse, but neither of the hybrid devices. Closer examination revealed that acceleration shortened *MT* for FingerMouse and Regular Mouse at all *W* levels. However for both hybrid devices, acceleration shortened *MT* with smaller *W* (4 and 8 pixels) but actually lengthened *MT* with larger *W* (16 and 32 pixels). This may be explained as such: In the ballistic stage of the pointing task where the whole hybrid device was being moved, the acceleration mechanism may have cognitively complicated users' mental model of controlling the finger and the hand simultaneously, resulting in performance loss. This was not the case for the final refinement stage, where only the finger plate was being moved. As a result, acceleration compromised *MT* performance with larger targets, for which the ballistic movement dominated the task.

Errors

The overall average error rate (number of errors made per trial) was 6.6%. There were significant main effects of *Device* ($F_{3,45} = 4.93$, $p = .005$) and *Acceleration* ($F_{1,15} = 7.89$, $p = .013$), but no significant interaction between the two ($F_{3,45} = 2.51$, $p = .070$). DualHybrid had fewest errors (4.7%), followed by FingerHybrid (6.3%), FingerMouse (7.4%), and lastly Regular Mouse (7.8%), as Figure 3 illustrates. Unsurprisingly, DualHybrid improved pointing precision by providing dual control granularities. However, it is interesting that FingerHybrid also outperformed the other two devices, even though the finger plate in this case had the same CD gain as the other two. This means that the coordination between the single finger and the whole hand resulted in users being able to control the *physical* movement more precisely than using either alone, which was likely a contributing factor for DualHybrid as well.

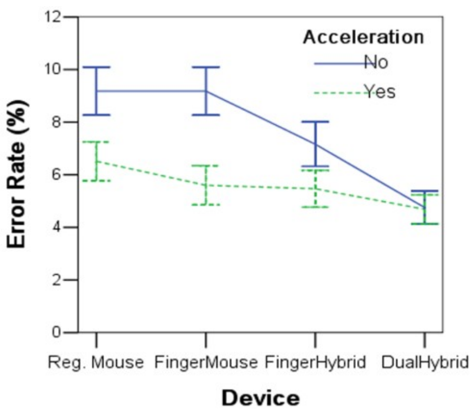

Figure 3. Error rate (std. err. bars).

Error rates without and with acceleration were 7.6% and 5.6% respectively. Acceleration improved pointing precision for all devices except DualHybrid, which already had built-in dual CD gains and therefore the extra space for improvement was less observable.

Fitts' Law Regression

We performed a linear regression for each of the 8 *Device* x *Acceleration* combinations to Fitts' law. Table 1 summarizes the results. Compared to the previous average *MT* analysis, *IP* (i.e. 1/*b*) is a more informative measurement about the fundamental information capabilities of the device, as it disregards *a,* the constant overhead mainly determined by the particular implementation (see [9] for a detailed discussion). Here both hybrid devices demonstrate higher *IP* values over Regular Mouse and Finger Mouse, both with and without acceleration. This further confirmed the advantage of their conceptual properties. Also interesting is that acceleration did bring considerable increment of *IP* for all devices, despite the fact that average *MT* remained the same for the hybrid devices. These show that the hybrid devices have a higher performance potential than implicated by the simple movement time analysis. On the other hand, the hybrid devices had higher *a* values (constant overhead), which were likely caused by the preliminary nature of the prototype.

Given the slightly higher error rates in our experiments, we also performed Fitts' law regression using effective target widths (W_e) based on the Welford correction of 4% error rate [8], and observed a similar trend on the resulting IP_e.

Device	Regular Mouse		Finger Mouse		Finger Hybrid		Dual Hybrid	
Acceleration	No	Yes	No	Yes	No	Yes	No	Yes
a (ms)	-839	-288	-601	-368	-320	0	-181	0
b (ms/bit)	649	495	625	527	539	470	499	460
r^2	0.951	0.969	0.980	0.963	0.976	0.993	0.986	0.994
IP (bits/sec)	1.54	2.02	1.60	1.90	1.89	2.13	2.00	2.17
IP_e (bits/sec)	1.50	2.03	1.56	1.93	1.88	2.06	1.96	2.05

Table 1. Fitts' law regression results.(IP_e: *IP* calculated using W_e)

CONCLUSION & FUTURE WORK

We have experimentally compared performances of pointing devices controlled by whole-hand, single-finger, and the combination of both. Results showed the hybrid devices improved pointing performance in terms of movement time, error, and bandwidth, especially for precise pointing. We feel that this type of hybrid pointing devices provide a new way to carry out fine precision pointing tasks alongside more regular mousing, offering the user with the best of both worlds. In the future, we plan to further investigate how the performance of the hybrid devices are affected by different relative gains between the finger and the hand, as well as design more informed acceleration mechanisms tailored for such devices. We are also excited in exploring new interaction techniques that leverage the extra two degrees-of-freedom input offered on the hybrid devices, in addition to using them as normal pointing devices.

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