Mushaca: A 3-Degrees-of-Freedom Mouse Supporting Rotation

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Abstract

Based on kinesiology research demonstrating that translation and rotation are inseparable actions in the physical world, we present *Mushaca*, a 3-degrees-of-freedom mouse that senses rotation in addition to traditional planar position. We present an optical realization of the Mushaca device based on two optical sensors and then evaluate the device through a series of controlled experiments. Our results show that rotation is indeed a useful input modality for a pointing device, and also give some insight into how users perceive the changing coordinate system of the rotating mouse and adapt to this change through kinesthetic learning.

Keywords: Rotational mouse, direct manipulation, evaluation, controlled laboratory study, hardware implementation.

1 Introduction

The mouse has been a standard component of the graphical user interface since its invention more than 40 years ago. However, many tasks, such as steering, drawing, calligraphy, and manipulation of 3D objects and maps often require more than two degrees of freedom for manipulation [1]. A common approach to achieve this is either through pure software techniques such as sliders and turn handles, or by combining the mouse with other devices such as the keyboard. However, these solutions often yield a high spatial offset as well as low degree of compatibility between how instruments are moved and how the object of interest responds [7]. This results in increased mental effort and completion times. Even integrating physical controls onto the mouse, such as additional buttons [12, 13] or a physical wheel that can be rolled [31, 36], is problematic because moving the mouse while interacting with these controls engages different muscle groups, causing awkwardness and delay.

In this paper, we introduce *Mushaca*,[1] a 2D pointing device based on a mouse that can also directly sense rotation around the vertical axis as a third degree of freedom (3DOF). We motivate the design of the Mushaca using research in kinesiology that has demonstrated that translation and rotation are inseparable actions in the physical world [20, 23, 37]: twisting your hand while moving it across a surface is both a natural and an effortless action. Furthermore, rotation is a largely untapped modality for the mouse ever since Engelbart's inception of the device [13], and allows software applications to adopt a control mechanism that has a higher degree of compatibility [7] than most other devices for many 3DOF tasks. Our prototype implementation of the Mushaca concept uses a pair of optical navigation sensors. We also briefly discuss a *MEMS version* that employs a 3-axis accelerometer and a gyroscope.

To validate the utility of the Mushaca device, we present results from several controlled experiments involving human participants using the device to perform various 3DOF tasks with and without a standard mouse as a baseline. Our tasks include maneuvering an object through a curved tunnel, matching two shapes in two dimensions, and matching two cubes in three dimensions. For each task, we compare the time taken for completion with Mushaca versus a standard mouse with a physical scroll wheel. Our results show that rotational input is beneficial, yielding an average of 35% lower completion time for each task when performed using the Mushaca device.

Rotating a mouse also rotates its coordinate system, which changes the meaning of translational (left/right versus up/down) motion. This in turn creates a mismatch between frames of reference in visual (display) and motor (device) space [38] that may pose a problem for a device where rotation is an input modality, such as the Mushaca. Not only must the user correct for this mismatch, which can be cognitively demanding, but large wrist angles resulting from such rotation may also be physically uncomfortable. To study both of these phenomena, we conducted an in-depth experiment studying the error associated with both of these cognitive and physical loads on the user. Our results show, not surprisingly, that pointing errors increase as wrist

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[1]Sanskrit for "mouse."

angles grow due to heightened cognitive and physical load. However, we also find that giving visual feedback of movement direction largely eliminates these errors despite such loads.

In the remainder of this paper, we first review the literature on pointing devices and the use of rotation for input. We then present the basic model for a 3DOF pointing device, as well as our prototype implementation. We report on four controlled experiments validating the device for different tasks. We close the paper with a discussion of the results, our conclusions, and our plans for future work.

2 Related Work

Despite a host of more advanced input devices being introduced over the years, the mouse remains the dominant input device for personal computers since its invention by Douglas Engelbart [13]. This can be attributed to its form factor, stability, position of buttons, and familiarity [6]. However, two-dimensional pointing is not always sufficient; augmenting the mouse with new input modalities such as a scroll wheel to provide additional degrees of freedom has been shown to improve user performance [17].

2.1 Pointing

Pointing is a canonical operation where users indicate a visual object of interest on a display through spatial targeting using a *pointing device* (where the mouse is one such), and can be modeled using Fitts' law [14, 26, 34]. This has enabled studies of pointing performance depending on device, precuing [16], as well as age [19]. Furthermore, much work has been devoted to "beating" Fitts' law [5], such as by predicting targets [30], changing target sizes [28], and making the targets sticky [9, 11]

2.2 3DOF Devices

Adding only a single additional degree of freedom to a mouse is often sufficient, and the now-standardized scroll wheel is one example of this. Similarly, Venolia's 3DOF mouse [36] uses a roller to provide the third degree of freedom. This enables new functionality, particularly for positioning and manipulating objects in 3D space. However, using the roller while dragging the mouse has been shown to be both cumbersome and unnatural [25]. In contrast, the rotation gesture for Mushaca is much more integrated and thus natural, building on kinesiology results emphasizing the close relationship between translation and rotation of the hand [20, 23, 37].

An early demonstration of a 3DOF mouse supporting rotation was shown by MacKenzie et al. [25]. Their device uses two mechanical balls to sense rotation, and the authors give several tasks, particularly for layout and drawing programs, where being able to change orientation would be useful. Naturally, the sensing mechanisms used to track mouse motion have advanced significantly since then. Mushaca, the 3DOF mouse we introduce, uses a pair of optical sensors (similar to the two-ball mouse). Furthermore, the paper does **not** present any formal performance results, whereas Mushaca is been extensively evaluated in this paper.

Almeida and Cubaud [3] propose a yawing mouse, realized using two laptop mice glued together side-by-side. They design their prototype explicitly for 3D window manipulation and conduct an informal pilot study on their work. In comparison, our work in this paper represents a technologically superior solution with higher accuracy. Furthermore, our studies look in more detail at a wider and more general set of user tasks.

Most recently, the Orienting Mouse [4] uses two optical sensors, just like the Mushaca, to sense rotation. However, the focus of this work is mostly on the technical implementation as well as some experimental applications for the device. In contrast, our present paper contains no less than three controlled experiments comparing the Mushaca 3DOF mouse to a standard mouse, and a fourth experiment studying the perceptual and biomechanical impact of rotating the Mushaca's coordinate system.

2.3 Multi-DOF Devices

Several devices supporting multiple additional degrees of freedom instead of just three have been proposed. The Rockin'Mouse [6] provides two additional degrees of freedom for manipulating objects in 3D. Although it demonstrates the need for a single device that performs well in 2D as well as 3D, the Rockin'Mouse does not take advantage of rotation on a 2D plane.

Similary, Hinckley et al. [18] presented a 6DOF mouse that relies on a camera and vision algorithms for sensing: the VideoMouse. Like the Rockin'Mouse, the VideoMouse retains the form factor of a conventional mouse because of the stability it offers and also to take advantage of the clutching mechanism to extend its range [6, 18]. However, even if the VideoMouse does offer six degrees of freedom, lifting the mouse from the 2D plane is typically interpreted as a clutch gesture, sacrificing the

Z-axis translation. Rotation around the vertical axis—as for our new Mushaca device—is supported, and the authors discuss biomechanical limits of wrist rotation, unintended rotations, as well as absolute and rate modes for controlling rotation.

Finally, very recent work proposed the Roly Poly Mouse [32], which is a rolling input device for 2D and 3D interaction. In comparison to the Roly Poly Mouse, which is hemispherical, the Mushaca device has the benefit of having a form factor similar to a standard mouse. The paper presents useful biomechanical results on comfortable rotation degrees using wrist motion. However, another significant difference between that work and ours is that we study perceptual aspects of changing coordinate systems due to rotation.

2.4 Beyond the Mouse

Many devices, primarily handheld, entirely forego indirect pointing devices such as the mouse in favor of touch interaction and related technologies, where rotation and translation is easily integrated [23]. Moscovich and Hughes [29] introduced two versions of cursor controlled with multiple fingers on a touchpad, allowing the user to concurrently move, rotate and change the scale of an object on a screen. Mushaca allows similar simultaneous rotation and translation of objects.

Bi et al. [8] study how to enable multiple degrees of freedom in pen-based interaction. They provide a rotational technique where rolling the pen allows for functionality such as scrolling, changing the thickness of a curve gracefully while drawing, and controlling zoom level in maps.

Finally, while strictly not related to pointing, Wigdor et al. [40] studied the impact of orientation on display space versus control space for physical visual environments. Additional studies by Keijser et al. [21] and Teather and Stuerzlinger [35] followed up on this work. This is relevant to this paper since rotational input for a mouse may also change the coordinate system for translation. We draw upon these works when studying the perceptual and biomechanical aspects of wrist motion for pointing.

2.5 Summary of Literature

Our work in this paper builds on all of the above 3DOF, multi-DOF, and esoteric pointing devices, particularly MacKenzie's 3DOF mouse [25], the yawing mouse [3], the orienting mouse [4], Rockin'Mouse [6], the VideoMouse [18], and the Roly Poly Mouse [32]. Furthermore, our work on perceptual and biomechanical aspects of rotational input (Section 5.8) is informed by studies conducted previous work that investigated comfort and accuracy for wrist motion. Our resulting Mushaca device seamlessly integrates rotation into the traditional mouse form factor using a straightforward optical implementation.

3 Mushaca: Basic Model

Input devices are instruments fitted with transducers for measuring physical parameters in several dimensions [10, 27]. The Mushaca device can be modeled as follows (Figure 1):

- **Translation:** relative movement deltas on the horizontal (left/right and up/down) axes (ΔX, ΔY);
- **Rotation:** relative rotation around the vertical (ΘZ); and
- **Button actuation:** button status for the left, middle, and right mouse buttons.

Clearly, the rotational input (ΘZ) is the differentiating factor compared to a standard mouse. As discussed above, we motivate this design by the fact that rotation and translation are inseparably integrated for the human hand [20, 37].

4 Prototype Implementation

We built a physical prototype of the Mushaca device using optical sensors and a 3D-printed shell (Figure 2). The physical dimensions of the Mushaca prototype is 65 mm (width) $\times$ 110 mm (length) $\times$ 35 mm (height). The optical navigation sensors are diagonally placed (55 mm apart) for maximum separation to yield high sensitivity. Translations are sensed from both the sensors, and the average of the two sensors is used. Rotations, on the other hand, are detected by sensing opposing motion readings from the sensors.

Our implementation uses a pair of ADNS5030 low power optical navigation sensor and a PSoC3 micro-controller for processing the data from the sensors. The configurable sensitivity of ADNS5030 allows for changing the sensitivity of rotation at the lowest level, making it possible to control the acceleration of the rotational input. With an optical sensor of sensitivity

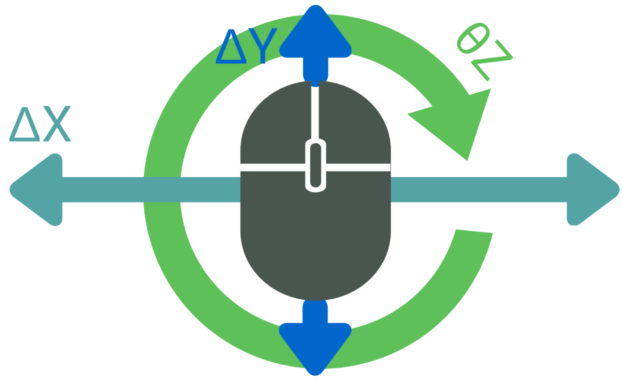


Figure 1: Mushaca model: ΔX, ΔY, ΘZ.

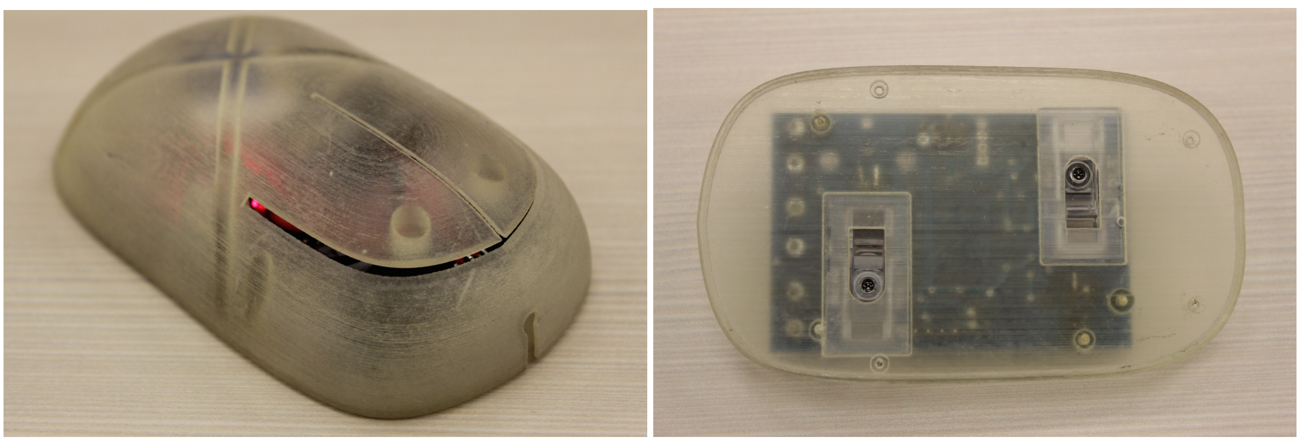


Figure 2: Wireless optical Mushaca with two optical sensors supporting a standard USB optical mouse interface.

of 1,000 CPI (counts per inch), we achieve 32 counts per degree, a very high resolution. The sensitivity (counts per degree) can also be adjusted at a fundamental level by adjusting the separation between the two sensors. The larger the separation, the larger will be the range of motion for a given angle of rotation and hence higher counts per degree.

5 Controlled Experiments

We conducted four user studies to evaluate the utility and limitations of rotational input for a mouse, split into two sets: realistic usages of rotation in comparison with a standard mouse (three experiments), and an in-depth experiment studying perceptual and biomechanical aspects of rotation for Mushaca. The realistic use-cases demonstrate how simultaneously being able to control both planar position and rotation can be intuitive to use and can improve user performance. They also show how direct rotational input can replace existing paradigms for rotation, such as using turn handle, sliders, or the scroll wheel on a standard mouse. Each experiment involved multiple trials with varying difficulty. We used completion time as the performance metric for comparing Mushaca with a standard mouse.

In the fourth experiment, we focused exclusively on Mushaca with no comparison to a standard mouse, and studied the impact of the mismatch between visual and motor space on participant accuracy. The goal of this experiment was twofold:

- Quantize errors due to mismatch between the visual frame of reference and rotating frame of reference of mouse.
- Understand the cognitive load and physical discomfort of twisting the wrist to manipulate an object on the computer.

5.1 Participants

We recruited 18 paid participants (15 male, 3 female) from the student population at our university (ages 21 to 28, average 25 years). All participants joined all four experiments. Participants were all self-selected volunteers with no skill requirements other than being proficient in using a computer mouse with their right hand. Each participant was compensated with $10 upon completion of the full study.

5.2 Apparatus

The experiment was conducted on an Apple MacBook Pro with 2.5 GHz processor, 4 GB RAM, and Mac OS X Version 10.9.2. Experimental applications were centered on a 19-inch LCD monitor at resolution 1440×900 (WXGA+). Experiment 1 used a window of size 640×360 pixels and Experiment 2 used one of 800×360; Experiment 3 and 4 were fullscreen. To interact with the applications, the participants were provided with a standard wireless mouse, and an optical version of Mushaca (which was also wireless). For the Mushaca device, all rotations were performed at a 1:1 gain; in other words, rotating the Mushaca one degree caused the corresponding visual object to rotate one degree. The reason for this choice was to maintain the high spatial compatibility of Mushaca.

5.3 Procedure

Participants were first given general instructions about each experiment and the trials. A demonstration of performing the actual task with a standard mouse and Mushaca was also given prior to the start of each experiment. Following the demonstration, participants were guided through four practice trials with each mouse. They were free to continue to practice as long as they felt it was needed. During the study, most participants were comfortable and took up the actual trials after four practice trials.

The first three experiments consisted of at most 12 trials with each mouse—standard mouse and Mushaca. The fourth experiment comprised of 48 trials with Mushaca. Participants were able to rest between trials. Each trial was timed; the timer started only when the participant performed the first click on the object of interest, and stopped when the participant finished the task successfully.

A complete session lasted up to 60 minutes, including training. After the completion of the trials, participants were asked to fill out a survey comparing Mushaca and standard mouse. They were also asked to provide any general feedback on Mushaca, the experiments, and rotational input.

5.4 Experimental Factors, Hypotheses, and Metrics

Each of the four experiments below used different experimental factors, hypotheses, and metrics for measuring participant performance; we discuss these for each individual experiment. Overall, performance metrics were all continuous (interval data), and experiments all involved between-subjects measures; for this reason, we chose to analyze the results using a repeated-measures analysis of variance (RM-ANOVA). Recall that RM-ANOVA, a parametric statistical test, relaxes regular ANOVA's independence assumption of cases to allow for between-subject designs. In all four experiments below, we determined that the normality and homoscedasticity assumptions were fulfilled using Shaphiro-Wilk and Bartlett tests, respectively.

5.5 Experiment 1 – 2D Object Matching

In this experiment, the task given to a user was to match two puzzle pieces on a 2D plane by aligning one piece on top of another. As shown in Figure 3, the two puzzle pieces differ in their orientation and are separated by a distance. Positions and rotations were uniformly randomized within the full window and $[-180°, 180°)$, respectively. The red piece was the target (fixed, but random position in each trial), while user was required to move and rotate the white one. Moving the piece was achieved by targeting it using the mouse cursor, pressing the left mouse button, and dragging the mouse. When the pieces aligned in both position and rotation, their outline changed color, and the participant completed the task by releasing the button, targeting the piece, and clicking the left mouse button.

- ***Factors:*** Device type (D):
  - *Standard mouse (S)* provides rotation input through a turning handle, translation by dragging.
  - *Mushaca (M)* provides simultaneous rotation (twisting the wrist) and translation (by dragging).
- ***Metrics:*** Completion Time (T) in seconds.
- ***Hypothesis:*** We formulate one hypothesis:

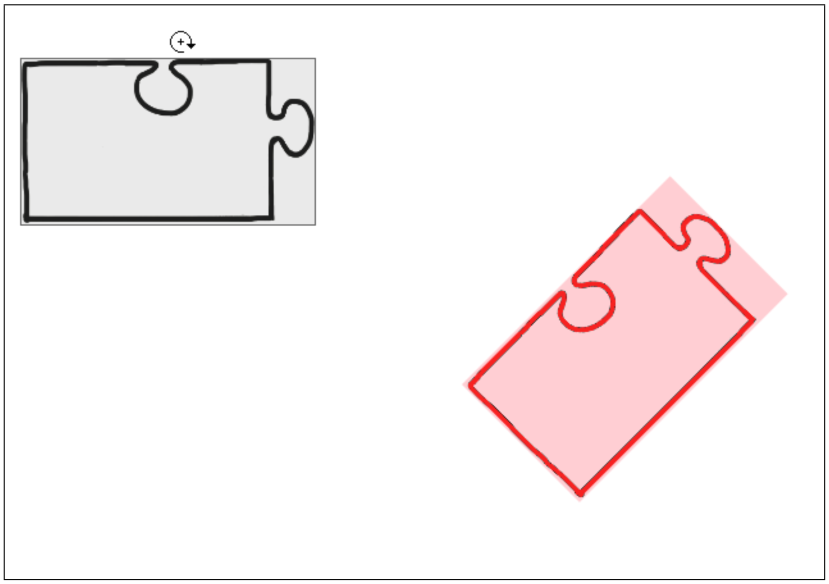


Figure 3: Screenshot of Experiment 1, where users were asked to match two puzzle pieces by clicking and dragging. The standard mouse requires turning a handle to rotate the object and dragging the piece to translate it.

H1 M *will be faster than* S. Having access to rotational degree-of-freedom in Mushaca will eliminate activation costs associated with enabling the turning handles for rotation. Rotating objects while they are being moved using Mushaca will enable easier and quicker matching of 2D objects than for the standard mouse.

- ***Results:*** We present the results in several forms below: quantitative completion times, and user behavior.
  - ***Completion time:*** We analyzed the completion time measurements using repeated-measures analysis of variance (RM-ANOVA). We found a significant effect of device type (D) on completion time ($F(1, 17) = 19.8, p < .001$). Figure 6(a) shows completion times averaged across all repetitions and all users. The average times were 7.6 seconds with Mushaca and 11.1 seconds with a standard mouse; a 46% improvement.
  - ***User Behavior:***

    Standard mouse – separate rotation + translation: With a standard mouse, most users first placed the white object approximately on the red one. By dragging the turn handle, they then rotated the white piece to match with the red piece. After rotating the white piece to a good degree of alignment, users further tried to reposition the object, then they switched back to rotation. This continued until the objects were matched.

    Mushaca – simultaneous rotation + translation: With Mushaca, users dragged the white puzzle piece and placed it on the red one. Nearly all the users rotated the object by twisting while it was being moved to the destination. Some users twisted their wrist, while a few other rotated the entire arm or a combination of both to rotate the object.

5.6 Experiment 2 – 3D Object Matching

In this experiment, users were asked to match two cubes in 3D, i.e. aligning one cube with another. As shown in Figure 4, the two cubes have different positions and yaw angles. For simplicity, the movement of the cube was restricted to a single axis (Y-axis), while rotation was about the yaw axis (Z-axis). Specifically, users were required to move and rotate the cube on the right side (blue border) to match it with the fixed cube on the left side (red border). Moving the piece was achieved by targeting it using the mouse cursor, pressing the left mouse button, and dragging the mouse. When the cubes were aligned, their outline changed color, and the participant completed the task by releasing the mouse button, targeting the cube, and clicking the left mouse button.

- ***Factors:*** Device type (D):
  - *Standard mouse* (S) provides rotation input using the scroll wheel, translation by dragging.

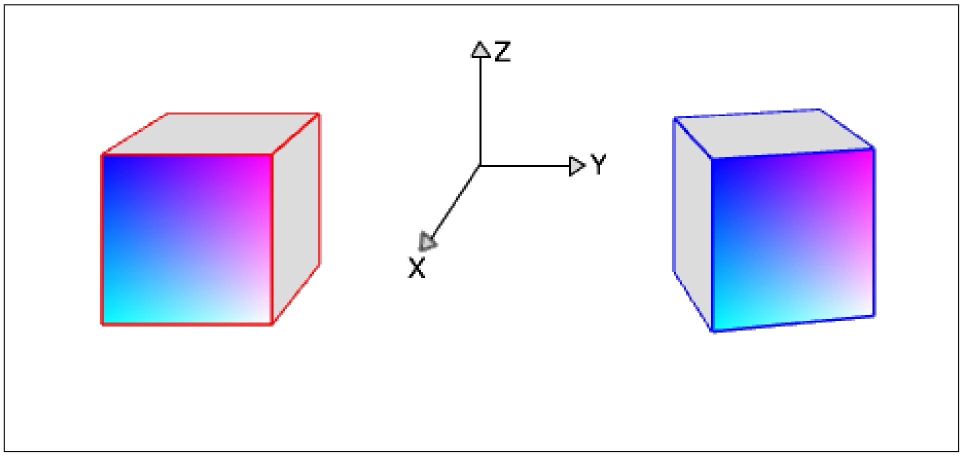


Figure 4: Screenshot of Experiment 2, were participants were asked to match two cubes in 3D.

 - *Mushaca (M)* provides simultaneous rotation (twisting the wrist) and translation (by dragging).

- ***Metrics:*** Completion Time (T) in seconds.
- ***Hypothesis:*** We formulate a single hypothesis:

H2 *M will be faster than S.* For a standard mouse, the scroll wheel rotates the cube, and dragging the mouse translates it. The muscle groups associated with these two operations are different and difficult to coordinate simultaneously. Most people will not scroll while dragging the mouse. With Mushaca, every wrist action directly translates to manipulations of the cube in both rotation and translation that eliminates activation costs and will result in lower completion time.

- ***Results:*** We present the results in several forms below: completion times, user behavior, and subjective feedback:
  - ***Completion time:*** RM-ANOVA analysis of the completion times (T) shows that the device type (D) has no significant effect on completion time ($F(1, 17) = 3.162, p = 0.0971$). Figure 6(b) shows completion times averaged across all repetitions and all users. The average times were 6.5 seconds with Mushaca and 7.6 seconds with a standard mouse, a 16.9% improvement for Mushaca.
  - ***User Behavior:***

    Standard mouse – rotation through scroll wheel: Most users stopped dragging the mouse to rotate the cube using the scroll wheel. They switched between movement of the cube and its rotation several times, until the task was complete. Four (out of 18) participants turned the wheel with their middle finger to rotate the cube while it was being moved. These participants self reported their regular use of a mouse and exceptional computer gaming skills.

    Mushaca – rotation through twist of the wrist: The majority of the participants simultaneously moved and rotated the cube.
  - ***Subjective feedback:***

    Ease and speed: Even though wrist rotation was directly compatible with the rotation of the cube, some users reported difficulty in coordinating simultaneous movement and rotation in 3D.

    Precision: Some users reported that they preferred the scroll wheel for rotation the cube due its precision. A few participants reported difficulty in making fine adjustments through wrist rotation.

    Physical demand: A small number reported discomfort using the scroll wheel for rotating the object. This was especially evident from the continuous use of the scroll wheel for larger angles.

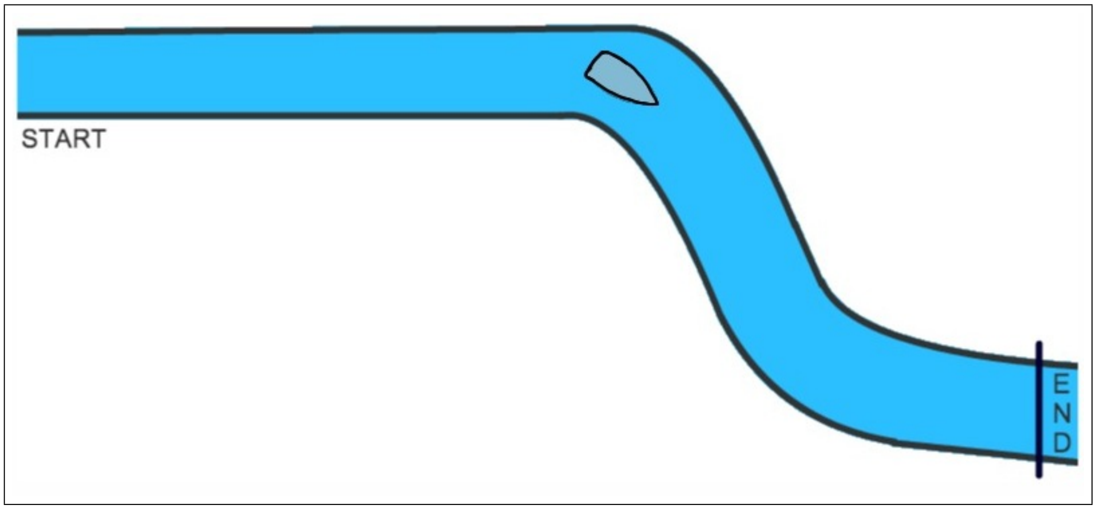


Figure 5: Screenshot of Experiment 3, where participants were asked to maneuver a boat through a river. This experiment showed no mouse cursor.

5.7 Experiment 3 – Steering with Rotation

In this experiment the objective was to steer a boat through a river, (from Start to End in figure 5) while avoiding collisions with the banks. The task involves not just moving the boat along the path, but steering through turns when necessary. This trial used no mouse cursor, allowing the user to instead control the boat directly using the mouse (no dragging needed). This was a crossing-based task, which automatically ended when the boat passed the goal line. Hitting one of the walls of the river reset the task from the beginning (also resetting the timer).

Many trajectory-based tasks such as drawing, writing, and calligraphy are possible with modern computers. However, the lack of a consistent way to input hand gestures makes tasks such as these unnatural. This experiment highlights how Mushaca could enable rotational input for such tasks.

- ***Factors:*** Device type (D):
  - *Standard mouse (S)* turns the boat using the scroll wheel, whereas dragging steers the boat.
  - *Mushaca (M)* translates its rotation to turns of the boat and its positional change to boat movement.
- ***Metrics:*** Completion Time (T) in seconds.
- ***Hypothesis:*** We formulate a single hypothesis:

  H3 *M will be faster than S.* As the boat is being steered by dragging Mushaca, it can be turned by simultaneously twisting the wrist. When steering through a continuously curving path, the continually available rotation input enables graceful turns of the boat to avoid the banks. With a standard mouse, switching between the scroll wheel (for turning the boat) and dragging (for moving it) will slow down the user. This effect is exacerbated when the path is serpentine.

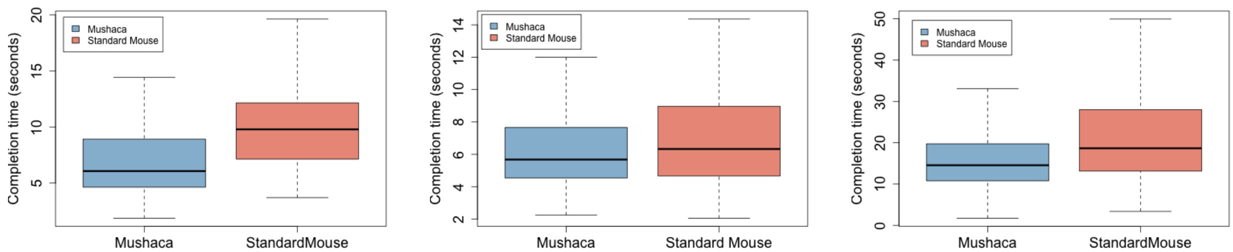
- ***Results:*** We present the results in several forms below: completion times, user behavior, and subjective feedback:
  - ***Completion time:*** RM-ANOVA analysis of the completion time shows that the device type (D) has a significant effect on the completion time ($F(1, 17) = 14.36, p < 0.001$). Figure 6(c) shows completion times. The average times were 16.4 and 22.6 seconds with Mushaca and a standard mouse, respectively, a 37.8% improvement in favor of Mushaca.
  - ***User Behavior:***

    Standard mouse - rotation through scroll wheel: Except for four participants (who scrolled with their middle finger while dragging the boat), all other participants stopped dragging to turn the boat using the scroll wheel. These four participants self-reported their exceptional computer gaming skills.

Mushaca - turn through twist of the wrist: Nearly all participants turned the boat while it was being moved to keep it parallel with the banks. Some users were so absorbed in the task that they did not realize that they ran out of mousepad space, and continued steering the boat to finish the task without clutching.

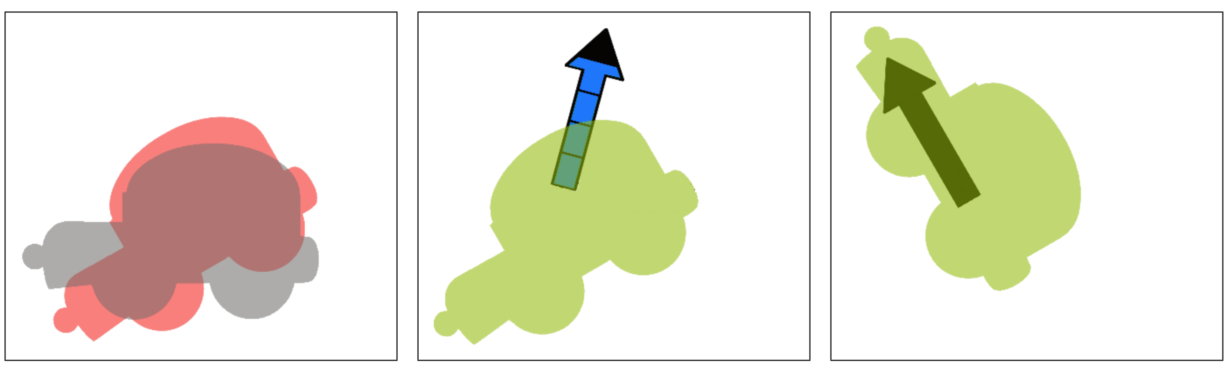
– ***Subjective feedback:***

Cognitive load: Three participants reported that they sometimes inadvertently turned the boat when they were only trying to move it using the Mushaca device. This may indicate that rotation and translation are sometimes difficult to separate.



(a) Matching 2D objects. (b) Matching 3D objects. (c) Steering with rotation.

Figure 6: Completion times for tasks in Experiment 1, 2, and 3, respectively. Error bars show standard deviations.



(a) (b) (c)

Figure 7: Screenshot from Experiment 4: (a) Rotating the gray car to match the red car. At correct rotation, the car turns green and is confirmed using a button press. (b) With visual feedback disabled, the car does not move, only the movement arrow fills up to indicate progress. (c) With visual feedback enabled, users see the car move in response to their input.

5.8 Experiment 4 – Effects of Rotation

The final experiment studied Mushaca in detail without comparison to a standard mouse. Instead, the participant is asked to first rotate a gray shape (a car) by twisting Mushaca until it matches with a red shape (Figure 7(a)). The angle between the cars vary from trial to trial. Once the cars are matched, the gray car turns green and the red car disappears. Users must confirm the alignment with a button press. Now users are shown an arrow instructing them to move the car in the specified direction (Figure 7(b)).

For half of the trials, the participant does not see the actual movement of the car or the cursor (no visual feedback) when dragging the mouse to follow the arrow. However, a progress bar fills up the arrow to provide an indication of progress (Figure 7(b)). For the other half of the trials, the green car moves as the mouse is dragged (Figure 7(c)), providing visual feedback. The direction for moving the car (the Arrow Angle A) is randomly chosen and is not dependent on the car orientation (the Car Angle C). This trial used no mouse cursor, allowing the user to instead control the object directly using the mouse (no dragging needed). This was a distance-based task that automatically ended when the green car had been moved the required distance (regardless of direction).

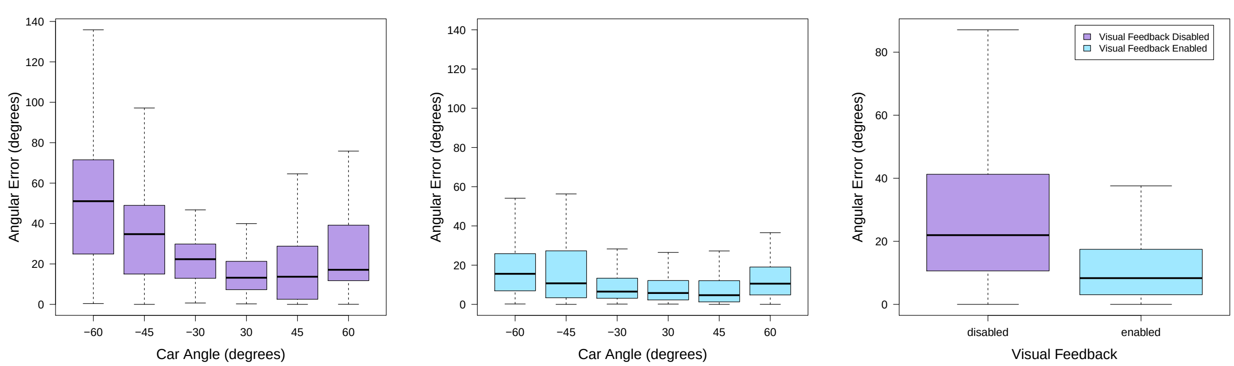
- ***Factors:*** We included the below factors in Experiment 4:
  - *Car Angle* (C)*:* determines the initial angle to which the wrist must be turned to match the cars.
  - *Arrow Angle* (A)*:* governs the direction in which the user must move the green car with a twisted wrist.
  - *Visual Feedback* (V)*:* Enabling and disabling visual feedback determines whether the green car is moved in response to user input.
- ***Metrics:*** Angular error (E) for the twisted hand movement, expressed as the absolute angular difference between the actual and intended destination of the green car.
- ***Hypotheses:*** We formulate three hypotheses here:

  H4 *Larger C results in higher E.* Increasing Car Angle increases the mismatch between the visual and motor space of the user. Beyond a certain angle, physical discomfort plays a role, increasing the error.

  H5 *Enabling V minimizes E.* Providing visual feedback activates kinesthetic feedback and proprioception cues associated with the user's muscle motor feedback system, correcting for angular errors.

  H6 *Certain combinations of C and A result in large errors.* Even though visual feedback reduces angular errors, physical discomfort associated with twisting the hand gives rise to angular errors.
- ***Results:*** An RM-ANOVA on the data from this experiment is in favor of our hypothesis. The Car Angle (A) has a significant effect on error ($F(5, 17) = 19.462, p < .001$). The boxplots for errors (Figure 8(a) and Figure 8(b)) show U-shaped pattern with minimum errors when the Car Angles are small (when the wrist has not twisted too much). Errors are higher for negative Car Angles, e.g. when a right-handed user twists the wrist inwards or counter-clockwise.

  The analysis also tells us that visual feedback has a significant effect on error ($F(1, 17) = 49.265, p < .001$). Comparing Figure 8(a) and Figure 8(b), the errors are clearly lower when visual feedback is enabled. We averaged the errors for all participants across all Car Angles, the box plot for which is shown in Figure 8(c). Reduction in error when visual feedback is enabled is easily noticeable.



(a) No visual feedback. (b) With visual feedback. (c) Overall error.

Figure 8: Angular error in Experiment 4 as a function of original car orientation. In (a), small car angles ($30°$ and $-30°$) result in smaller angular error (Tukey HSD, $p < .05$). Enabling visual feedback (b) results in significantly lower error (RM-ANOVA, $p < .001$). Error bars show standard deviations.

6 Discussion

Summarizing the results, we see the following:

- Matching 2D objects was significantly faster with Mushaca when compared to a standard mouse (confirming **H1**);
- 3D object matching was *not* significantly faster with Mushaca than for a standard mouse (rejecting **H2**);

- Steering objects through curved paths can be performed faster with Mushaca than a normal mouse (confirming **H3**);
- The rotating frame of reference of Mushaca affects the users interpretation of directions, resulting in erroneous mouse movement (confirming **H4**);
- Users learn through proprioception and get accustomed to the changing coordinate system if proper visual feedback is provided; Figure 8(b) confirms **H5**; and
- Twisting the wrist to rotate virtual objects introduces physical restriction on mouse motion resulting in errors that cannot be completely eliminated (confirming **H6**).

6.1 Explaining the Results

Given the above results, let us now look at each experiment and discuss them in detail.

6.1.1 Experiment 1: 2D Object Matching

With a standard mouse, participants constantly switched between rotation (turning handle) and position control (dragging the mouse). Jumping between controls several times not only had activation costs, but also made the process clumsy.

Physical manipulations on Mushaca were directly translated to the reaction of the 2D object, identical to manipulating objects in the real world with hands. Furthermore, manipulations through the simultaneously available rotational and translational degree of freedom made the process easier, resulting in lesser completion time. However, one aspect that may have had a detrimental effect on Mushaca was the need for participants to keep a button pressed while rotating the device, since this is conceivably more difficult than with a straight wrist for the standard mouse.

6.1.2 Experiment 2: 3D Object Matching

Similar arguments hold for 3D object matching. The bulk of the participants simultaneously moved and rotated the cube, resulting in slightly faster (but not significantly so) alignment of the cubes. Even though wrist rotation is directly compatible with the rotation of the cube, some users struggled with simultaneous translation and rotation in 3D. Due to increased cognitive load, the performance improvement was not significant ($p = 0.0971$). Similar to Experiment 1, the need to keep the left button pressed while rotating and dragging the Mushaca may also have impacted performance.

The precision offered by the scroll wheel in a standard mouse for rotating the cube was evident from users performance during the study. Although Mushaca is capable of detecting very small angular changes (1/32 of a degree), users reported that fine adjustments by twisting the hand was difficult. Further work is needed to understand the precision possible for rotational input using the wrist.

6.1.3 Experiment 3: Steering with Rotation

The majority of the participants took full advantage of rotation to turn the boat, even with very little training. They learnt to steer the boat using the simultaneous degrees of freedom, resulting in smooth motion and faster task completion. Unlike Experiments 1 and 2, participants in this experiment also benefited from not having to press a button while rotating the Mushaca device.

6.1.4 Experiment 4: Effects of Rotation

As the angle between the cars increase, the mismatch between the frame of reference seen on the display and that of Mushaca (held by the user) increases. When instructed to move in a given direction by showing an arrow, most users were unaware of the rotated frame of reference of the device, and their movement was hence erroneous, as seen in Figure 8(a) and Figure 8(b). From the same figures, we can even see that the errors are significantly higher for negative angles, that is when a right-handed user rotates his/her wrist to the left (counterclockwise). Intuitively, when the wrist has rotated left, physical discomfort is prominent.

Comparing Figure 8(a) and Figure 8(b) clearly proves our hypothesis that visual feedback reduces angular errors associated with the rotating frame of reference. The same argument is given by Figure 8(c) as well as our statistical analysis.

6.2 Generalizing the Results

The three scenarios covered by the user study constitute simple tasks such as 2D manipulations, 3D object manipulation, and steering objects. Studies have shown that the time taken to rotate real world objects is much faster compared to rotating virtual objects, attributing to the frame of references effects [39]. A 3DOF device such as the Mushaca may be able to eliminate some of these differences. Beyond just simple manipulations, the third degree of freedom in Mushaca can be used to control the scale of images, zoom level of maps, changing thickness in calligraphy, panning control in first-person games, and so on. Poston and Srikanth [33] describe a few such applications that can benefit from the third degree of freedom that devices such as the Mushaca provide.

The choice of participants in our study may also have an impact on the results. All the participants were randomly selected engineering students from our university. Most of them were regular users of computers, a few had considerable computer gaming experience. Some users reported difficulty in coordinating simultaneous rotation and translation with Mushaca. We believe that artists and designers could achieve this with ease, possibly due to their dexterity and interpretation of the 3D space. We intend to study this through a follow-up study. It would also be interesting to study how a person with no computer mouse experience uses Mushaca.

Although twisting or rotating the wrist is a natural process, rotating beyond a certain degree is physically strenuous due to anatomical reasons compared to moving of a mouse. A couple of users reported physical discomfort, and even mentioned the possibility of developing soreness due to wrist rotation. A direct mapping between the rotation of Mushaca and the rotation of the object of interest might produce awkwardness for large angles. One approach might be to accelerate the rotational input to minimize such effects.

The Mushaca device is based on matching the properties of the input device to the task properties—specifically, matching twisting of the wrist to some appropriate rotational movement in the interface. It could always be argued that attempting to match physical device properties to tasks in such a way either yields devices that are insufficient or overly specialized in nature. Instead, the choice for interaction design in recent years has been to design interaction techniques that work with general pointing devices, such as object handles and manipulators that allow for configuring complex object properties. This has been the preferred strategy instead of adding buttons, axes, or complex gestures to the mouse. However, this trend is partly changing with the advent of touch computing, which support an order of magnitude more complex interactions, such as pinching, swiping, and dwelling. Furthermore, we argue that the rotational axis provided by the Mushaca device is particularly useful since it merely augments the current capabilities of the ubiquitous mouse without requiring entirely new interaction styles.

Our results on how participants perceived as well as performed pointing when wrist motion was involved has many similarities to those of Wigdor et al. [40] and follow-up works [21,35]. While these earlier works all studied physical environments where control and visual spaces did not align, this turns out to be similar to the Mushaca device in Experiment 4 where the initial rotation causes the participant's frame of reference to change. For example, Wigdor found that participants were unable to correctly identify the best-performing physical orientation, which is supported by our finding that no visual feedback gave rise to higher errors because participants were unable to correct them. Seen in this light, our overall results seem to support Wigdor's conclusion that physical comfort may be more important than accuracy for these situations.

Finally, we opted not to perform a rigorous Fitts' Law [14, 15, 24] or Steering Law [1, 2] experiment for the Mushaca because we were primarily interested in practical usage of the device. However, our informal testing indicates that an angular formulation of Fitts' Law [22] could be applied to the Mushaca. We leave such experiments for future work.

6.3 MEMS Implementation

In addition to the optical implementation, we also built a MEMS (microelectromechanical system) version of the Mushaca (Figure 9). It realizes the same Mushaca interface, yet using different technology.

The MEMS version of Mushaca uses two different sensors for sensing translation and rotation: a 3-axis accelerometer to compute movements along X and Y axes, and a gyroscope to measure rotation. Filtered data from the accelerometer is integrated twice to estimate the X and Y positional changes. For rotation, an integration of the angular rotation rate provides the angle increment by which the mouse was turned.

Several factors make the MEMS version challenging to implement, including drift errors in the accelerometer, continuously changing DC offset, isolation of gentle motion from noise, and sloping surfaces.

Figure 9: Wireless MEMS Mushaca with accelerometer and gyroscope supporting a standard USB optical mouse interface.

7 Conclusion and Future Work

We have presented *Mushaca*, a pointing device that supports rotation, which kinesiology has shown is inseparably integrated with the traditional translation measured by a mouse [23]. We created two hardware prototypes to realize our model of a mouse with rotation input: one optical, and one using MEMS transduceers. Through controlled user studies we have shown that users were easily able to adopt rotational input in Mushaca with minimal or no relearning. Furthermore, we found that visual feedback can eliminate angular errors associated with the rotating frame of reference.

In general, we believe simple rotation input introduced through Mushaca could become a standard feature of the ubiquitous mouse. Our rotation-sensing devices open up a number of possibilities, such as for gesture recognition, target acquisition, and other input devices such as a pen or stylus. We also intend to explore how users perform when the frame of reference in display space and motor space are merged.

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