

TNT: Improved Rotation and Translation on Digital Tables

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ABSTRACT

Digital tabletop systems allow users to work on computational objects in a flexible and natural setting. Since users can easily move to different positions around a table, systems must allow people to orient artifacts to their current position. However, it is only recently that rotation and translation techniques have been specifically designed for tabletops, and existing techniques still do not feel as simple and efficient as their real-world counterparts. To address this problem, we studied the ways that people move and reorient sheets of paper on real-world tabletops. We found that in almost all cases, rotation and translation are carried out simultaneously, and that an open-palm hand position was the most common way to carry out the motion. Based on our observations, we designed a new set of reorientation techniques that more closely parallel real-world motions. The new techniques, collectively called TNT, use three-degree-of-freedom (3DOF) input to allow simultaneous rotation and translation. A user study showed that all three variants of TNT were faster than a recent technique called RNT; in addition, participants strongly preferred TNT.

CR Categories: H.5.2. [Information Interfaces and Presentation]: User Interfaces—Interaction Styles.

Keywords: rotation, translation, orientation, tabletop displays, tabletop groupware.

1 INTRODUCTION

Digital tabletop displays have recently attracted considerable attention from HCI researchers. Tables are interesting settings for computational work because they are common, they enable rich interaction with tools and artifacts, and they naturally support collaboration [7]. There are a number of challenges in designing systems and interaction techniques for tabletops; one of these is that, unlike vertical displays, tabletops do not have a predefined orientation. Since users' perspectives change as they move around the table, designers cannot make assumptions about the preferred orientation of artifacts—there is no clear up or down, left or right. Therefore, tabletop applications must allow users to easily move and reorient objects: towards themselves for reading and manipulation, and towards others around the table during group activities.

Reorienting artifacts has two main components—translation, where an artifact is moved across the workspace, and rotation, where an artifact is turned so that it faces a particular direction. Rotation and translation techniques for tabletops have only recently been considered in detail, and it is still unclear how the reorientation of artifacts can best be supported. Many systems use techniques that are similar to those seen in desktop applications—they use two-degree-of-freedom (2DOF) input, and divide rotation

and translation into two separate gestures (e.g. [14,17,18,16]). Other techniques make use of finger-based input, styluses, and pens (e.g. [10,20,2]). However, none of these techniques closely parallel reorientation on real-world tabletops, and with the exception of RNT [2], their accuracy and efficiency have not been empirically evaluated.

Our goal in this research was to build a better reorientation technique for digital tabletops, and to base our technique on a better understanding of the ways that people rotate and translate objects in the real world. We observed people while they carried out translation and rotation tasks using sheets of paper on real tabletops, and we recorded and analyzed their movement patterns. We found that current interaction techniques do not reflect common real-world interaction styles. The study showed that rotation and translation are usually carried out simultaneously, and that people most often move objects with an open-palm hand position.

We developed three new interaction techniques to allow interaction with artifacts on tabletops in a way that closely mirrors the most common movement patterns that we saw in our observations. The techniques – collectively known as TNT – use 3DOF input to support simultaneous and fine-grained control over both rotation and translation. The new techniques were prototyped using a Polhemus Fastrak; the three variants use different input configurations (hand, finger, or tangible block), and differ slightly in their algorithms.

We evaluated the new techniques in a study that compared TNT with RNT, a 2DOF tabletop interaction technique [2]. In both precise and imprecise tasks, participants were able to carry out reorientation tasks significantly more quickly with the TNT techniques than with RNT. Participants were fastest using the tangible-block version of TNT, and the whole-hand version of TNT was second fastest. Participants also preferred TNT, ranking TNT-block highest and RNT lowest.

2 REORIENTATION ON TABLES

The rotation and translation of information artifacts is supported in many applications, particularly in those that support image editing, drawing, and design. On desktop systems, input is usually restricted to a 2DOF device like the mouse, and so rotation and translation are often divided into two separate gestures or commands [e.g. 4].

Orientation is an important part of tabletop work, particularly in collaborative activities where several people view the workspace from different positions [3,21,22,23]. Kruger et al. [3] point out that the orientation of objects helps groups to comprehend information, to communicate, and to coordinate work. Pinelle et al. [23] indicate that object orientation can often pose a challenge to groups since only one person may be in a position to view and interact with an object, but several people may need to work with it concurrently.

Many tabletop systems provide support for reorienting artifacts, and reorientation can be supported in several main ways: 1) by rotating the workspace, 2) by automatically reorienting artifacts in the workspace, or 3) by allowing users to change the orientation

of individual artifacts. Some systems allow users to rotate the entire workspace and its content (e.g., [19,16,15,6]). For example, Magerkurth et al. [6] developed a game that rotates the workspace so that it faces each player during their turn; similarly, the Personal Digital Historian allow users to view and manipulate photos and to rotate the entire tabletop workspace [16,19].

Some tabletop applications automatically rotate artifacts in the workspace. Ryall et al. [12] describe a system that allows groups to compose poetry using “magnetic” poetry tiles, and the tiles are automatically reoriented so that they face the closest edge of the table. The InfoTable [9] determines users’ positions around the table, and when they move an artifact, it automatically rotates it so that it faces them.

Most tabletop systems allow users to change the orientation of artifacts using direct manipulation interaction techniques (e.g. [11,20,10,14,17,18]). Rogers et al. [11] describe a system that allows users to collaboratively design a calendar with other co-present individuals. The system allows users to drag and spin artifacts in the workspace using their fingers. Another technique, called the “corner to rotate” technique by Kruger et al. [2], is used to support rotation and translation in several tabletop systems (e.g., [14,17,18,16]). The user clicks and drags an object to translate it. To rotate an object, they select it, touch a corner, and then turn it around an axis located at the center of the object.

Several researchers have investigated supporting rotation using input devices that use more than two degrees-of-freedom. Fitzmaurice et al. [1] describe tangible bricks that can be used to move and rotate virtual objects. Several other devices also support rotation, including the 3-D Ball [27], the Tracker [27], Arcball [25], and Virtual Sphere [26]. While they were not developed specifically for tables, they are relevant nevertheless since they can combine translation and orientation into a single gesture.

Recently, several researchers have proposed generalizable rotation and translation techniques for tabletop systems. Ringel et al. [10] describe a rotation and translation techniques called “relocate” and “reorient” where people use their fingers to interact with artifacts, using a style similar to that of “corner to rotate.” Wu and Balakrishnan [20] describe a single-finger tap and drag translation technique. They also describe a two-finger rotation technique, where the user places a finger on an object to establish the axis of rotation, and the second finger is used to rotate the object around the axis finger.

Many existing tabletop rotation and translation techniques are awkward when compared with reorientation tasks on real world tables. Users must switch between rotation and translation modes, and often must interact with the object several times before it is positioned properly (e.g., [14,17, 18,16]). While new interaction techniques are promising [10,20], they have not been rigorously evaluated, and it is not clear whether they are better than existing techniques. The only new technique that has been tested against standard two-step rotation and translation is Kruger et al.’s RNT [2]. Since we will later compare our new techniques with RNT, we provide more detail on it next.

3 ROTATE ’N TRANSLATE

Rotate ’N Translate (RNT) is a tabletop interaction technique that combines rotation and translation into a single gesture [2]. It uses two degrees of freedom, so it can be used with common input devices such as mice and pens. Kruger et al. showed that users are able to carry out targeting tasks on tabletop more quickly and accurately using RNT than they can with the “corner to rotate” technique that is used in many tabletop systems.

In RNT, the artifact is partitioned into two regions (Figure 1). By clicking in the circular region in the center of the artifact, the user can drag the artifact around the workspace (translate only). By clicking outside of the circle, the user can rotate and translate

the artifact using a single gesture. When the user clicks in this region, the RNT algorithm identifies a “control point.” Translation and rotation begin simultaneously, and artifact translation follows the movement of the pointer. Figure 1 shows an artifact that has a control point in the lower right initially; the arrow shows the direction of pointer movement. While the artifact is translated, it rotates around the control point. As the translation progresses, the control point pivots in the direction of the translation until most of the artifact is behind it, and the artifact is then “pulled” by the control point. In Figure 1, the control point rotates upward in the direction of the translation.

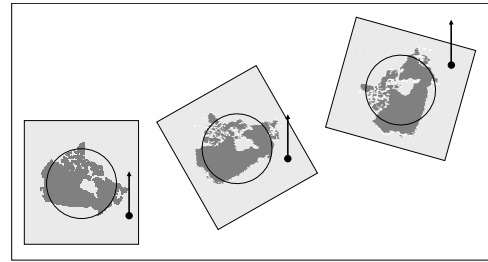


Figure 1. RNT. A control point is selected in lower right, and the artifact rotates counterclockwise while it is translated upward (Adapted from [2]).

4 OBSERVATIONAL STUDY

Tabletop systems often blur the traditional boundary between display and input, and many tabletop systems allow users to directly manipulate artifacts using styluses, sensors, or other tangible interaction techniques (e.g., [10,20,2,1,7,8]). In part, this may be due to the traditional affordances of a table—it is a work surface where people physically reach for and manipulate objects. When the table is used to project a digital workspace, it seems natural that users should still be able to directly interact with the artifacts that are arrayed before them. This is further supported by Ware and Rose [24], who found that placing the hand in the working space improves users’ efficiency at reorienting virtual artifacts. Also, unlike vertical displays, the tabletop display is the input space, and input devices such as mice and trackballs can occlude artifacts and controls.

In this research, we developed interaction techniques that allow users to directly interact with artifacts on tabletop systems. Prior to developing the techniques, we carried out an observational study of the ways that individuals rotate and translate sheets of paper on a real-world tabletop. We felt that by developing a detailed understanding of the ways that people carry out these tasks in the real world, we would be able to develop interaction techniques that closely mirror users’ movements, providing potential benefits, including: 1) reduced training times, 2) reduced cognitive load, and 3) easy recognition of action by collaborators.

In our observations, we established a set of parameters to help ensure that the data we collected would be useful in developing rotation and translation techniques. We chose a task that had similar characteristics and a comparable style of interaction to the 2D world of a tabletop display. We asked 10 participants to transfer sheets of paper containing printed text across a tabletop so that they could be read by others sitting at the edges of the table. We allowed participants to select any transfer technique that they wished; however, we asked them to keep the pages in contact with the table (similar to digital interactions on a flat, two-dimensional surface).

We analyzed videotapes of the sessions to identify the movement patterns that were used during each transfer. By far, the most common movement technique was to extend the fingers and

to transfer the paper using either the fingers or the palm of the hand (see Figure 2; seen in 81% of transfers). In the rest of this paper, we refer to this as an open palm transfer. Rotation and translation movements were almost always combined, where individuals rotated objects while they translated them. Furthermore, participants often touched a page several times during a single transfer, and repositioned their hand once they reached the limit of the available range of motion in the involved joints (usually the wrist).

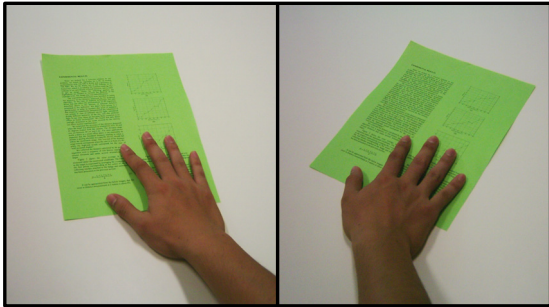


Figure 2. Open palm transfer using sheet of paper

5 DESIGN CONSIDERATIONS

The observational findings provided us with substantial guidance in developing the new rotation and translation techniques. From our analysis, we identified a set of requirements for ensuring that techniques closely approximate real-world interaction patterns. These are:

1. Combine rotation and translation so that separate gestures are not needed to reorient artifacts.
2. Support open palm transfer where fingers are extended and object is moved with the palm or fingers.
3. Support multiple touches so that users can release an artifact and reposition their hand during transfer.
4. Allow gross movements across the table and small, precise adjustments.

The first and second requirements strongly influenced our choice of technologies. The two main components of the open palm technique are: translation of the object across a Cartesian plane, and rotation of the object about an arbitrary axis. Since the two components needed to be combined into a single gesture, a 3DOF input device was needed.

6 INTERACTION TECHNIQUES

We developed three new interaction techniques for reorienting projected artifacts on tabletop displays. They were prototyped with a Polhemus Fastrak system, which has sensors that can track six degrees of freedom, but we only used three degrees in our techniques (X, Y, and Yaw). The initial technique, TNT-hand, was based on observational findings from real-world tabletop tasks. The other two techniques, TNT-block and TNT-hybrid, are similar to TNT-hand, but have slight modifications in the sensor presentation or algorithm.

6.1 TNT-hand

The TNT-hand technique is similar to the open hand technique, which was the most frequently used technique that we saw during our observations. It combines translation and rotation so that users can carry out both actions using a single movement. In TNT-hand, the user wears a ‘finger sleeve,’ containing a Fastrak sensor, on their index finger. The sleeve is worn so that the sensor is positioned on the palmar surface of the index finger.

The user selects an artifact by extending their fingers and lowering their hand onto the artifact. The object is selected when the sensor sleeve comes into physical contact with the table. Once the artifact is selected, the user can move and rotate the object by sliding their hand across the tabletop (Figure 3). The user deselects the artifact by lifting their hand from the table.

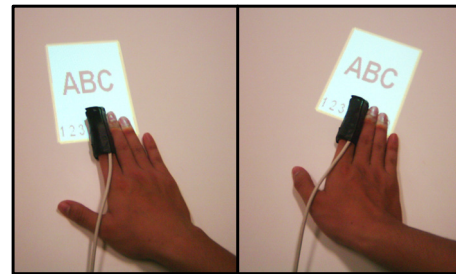


Figure 3. TNT-hand technique

When the artifact is selected using this technique, the system identifies a starting sensor position. All coordinates are based on the assumption that the hand is parallel to and in contact with the table (a prerequisite of selecting an artifact). The starting position includes three variables: an x coordinate, a y coordinate, and the rotational angle of the sensor. As the hand moves across the table, new x and y coordinates are used to determine the new location of the artifact, and the representation is dynamically redrawn during the movement to provide the user with visual feedback. When the hand (and sensor) is rotated away from the starting rotational angle, the artifact rotates to follow the hand. When the hand is raised away from the table, the artifact is deselected, and the artifact stays in its current location.

6.2 TNT-block

The TNT-block technique uses the TNT-hand algorithm, but the user interacts with the sensor differently. The sensor is contained in a cylindrical ‘block.’ The block that we developed is plastic and has a height of 4.25 cm and a diameter of 5.25 cm. We chose a block with a cylinder shape since it does not have a clear orientation, which frees the user from worrying about the alignment of the block when selecting an artifact (see Figure 4).

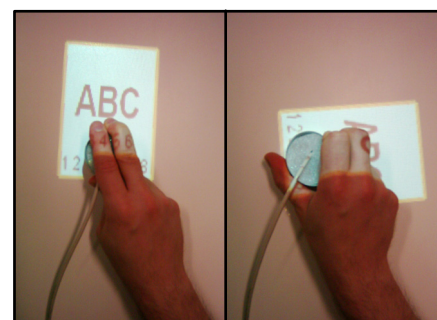


Figure 4. TNT-block. Left: sensor positioned on artifact. Right: Large rotation angle by twisting block.

We developed the TNT-block technique to make it easier for users to manage large rotational angles. Wrist range of motion is limited to approximately 30 degrees of ulnar deviation (toward little finger) and 20 degrees of radial deviation (toward thumb) [5]. Individuals can incorporate other joints into rotational movements (e.g., shoulder and trunk), but when rotational angles of greater than approximately 90 degrees are needed, they have to reposition their hand when they reach the limits of the available

range of motion. Since the cylindrical block is relatively small and fits easily between the fingers, we felt that it would allow users to achieve large rotational angles by rolling it between their fingers in a single movement. Similarly, since the technique implements the TNT-hand algorithm, we felt that it could still achieve many of the benefits that we hoped to see through designing naturalistic interaction techniques.

6.3 TNT-hybrid

The TNT-hybrid technique combines two tabletop interaction algorithms: TNT-hand and RNT. TNT-hybrid uses the same sensor setup as TNT-hand, where the user wears a Fastrak sensor in a sleeve on the index finger. The technique uses different interaction algorithms in different regions of artifacts. On the outer edges of the artifact, the technique uses the RNT algorithm. In the center of the artifact, the technique uses the TNT-hand algorithm. The two regions are differentiated using a semi-transparent circle that is projected onto the artifact (see Figure 5).

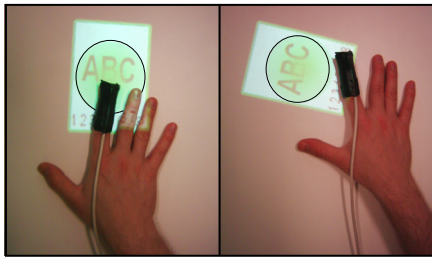


Figure 5. TNT-hybrid. Left: Sensor in TNT-hand region. Right: Large rotation angle using RNT region.

We developed the TNT-hybrid technique for the same reason that we developed the TNT-block technique—to help users to overcome limitations in upper extremity range of motion that

make it difficult to achieve large rotation angles. RNT allows significant rotation without repositioning the upper extremity. By combining the techniques, we hoped to provide users with a mechanism for achieving large angle rotation while retaining some of the benefits that could potentially be achieved through using a naturalistic interaction style.

7 EMPIRICAL EVALUATION

We carried out a controlled study in which we asked participants to complete a series of reorientation tasks. Participants carried out tasks with the three TNT techniques and also with RNT. We included RNT in our evaluation to provide a baseline since it is an established tabletop rotation and translation technique.

7.1 Participants

Twelve participants, 11 male and 1 female, were recruited from a local university. Participants ranged in age from 19 to 40 years (mean 26.25). All participants were right-hand dominant. All were regular computer users (more than 8 hours/week), and only one participant had previously used a tabletop display system.

7.2 Apparatus

The experiment was conducted on a top-projected tabletop system using an Epson multimedia projector running at 1024x768 resolution. The projector is connected to a Pentium 4 Windows XP computer. The table was custom-built and is not touch sensitive; the table surface is 125cm x 160cm and has a display area of 115 cm x 155 cm. Input was provided using a Polhemus Fastrak system, (our techniques used only three of the six available degrees of freedom). The sensor setup uses two different configurations as described above: the finger sleeve (TNT-hand, TNT-hybrid, and RNT); and the cylindrical tangible block (TNT-block).

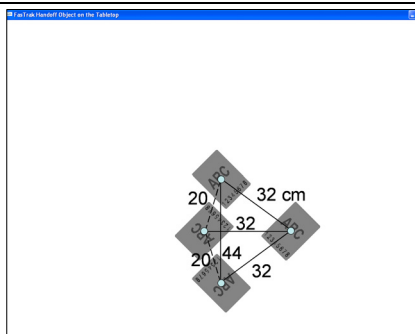


Figure 6. Task 1 targets. Solid lines show transfer paths. 4 rotations shown.

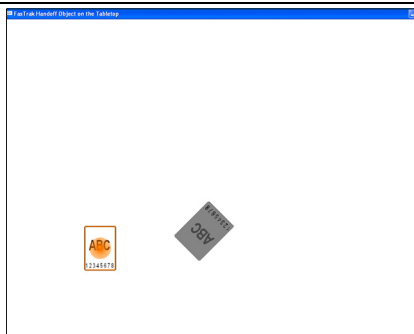


Figure 7. Task 1 experimental setup showing artifact (left) and target (right).



Figure 8. Task 1 trial using TNT-block technique

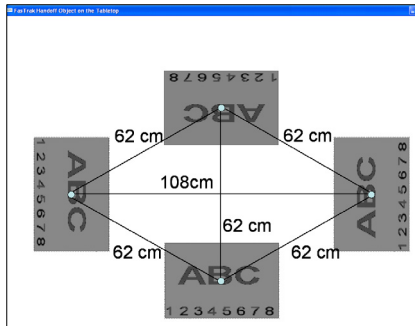


Figure 9. Task 2 targets.

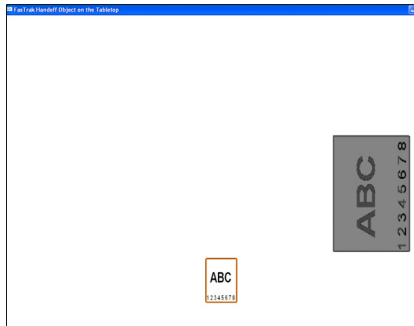


Figure 10. Task 2 experimental setup.



Figure 11. Task 2 trial using TNT-hand.

7.3 Tasks

Two tasks were designed to cover common reorientation scenarios on tabletops. The first task evaluated participants' performance in carrying out precise targeting in their personal territory. The personal territory is a region that is directly in front of the user, and it is usually used to carry out individual work activities [13]. The second task evaluated performance in carrying out imprecise targeting at the edges of the table. This task simulated collaborative handoff tasks, where users transfer artifacts to others sitting around the table.

7.3.1 Task 1: Targets in Personal Territory

This task compared techniques during precise targeting trials carried out in close proximity to the user. During each trial, participants transferred a small rectangular artifact (102x124 pixels, 16x11cm on the table surface) into a target (112x142 pixels, 17.5x12.5cm) with a different orientation (see Figures 6,7,8). To successfully move the artifact, the participant had to reorient it so that its rotation was within five degrees of the target's rotation, and so that it fit completely within the target.

Initially the artifact was oriented toward the participant, and was positioned at one of four target locations (Figures 6,7). Four different rotations were used for each target: 45, 135, 225, and 315 degrees (all angles are shown in Figure 6). Figure 6 also shows the transfer paths that were used in the task. Each solid line indicates a pairing between a target and an artifact starting position. Paths are bidirectional, so there were a total of 8 paths. For each of the 8 paths, all 4 target rotations were included, and 3 trials were carried out for each combination (for a total of 96 trials per task). The order of target / start position pairs was randomly determined.

7.3.2 Task 2: Targets at Edges of Table

This task compared the techniques in imprecise tasks where an artifact was moved into large targets at the edges of the table. The task simulates collaborative situations, where users sit around the edges of the table, and where artifacts are shared by the users. The targets were allowed a wide variance in rotation since users do not usually need to be precise when handing an artifact to others. During each trial, participants transferred a small rectangular artifact (102x124 pixels, 16x11cm on the table surface) into a large target (179x313 pixels, 27x41cm) with a different orientation (Figures 9,10,11). To successfully move the artifact, the participant had to reorient it so that its rotation matched that of the target within 45 degrees, and so that it fit within the target.

Unlike task 1, orientation for each target was fixed. Since the task was intended to simulate a collaborative situation, each target was oriented so that a user sitting at the nearest edge of the table could read the text that was printed on the target, and the targets were rotated at 0, 90, 180, and 270 degrees relative to the participant. The target positions and orientations are shown in Figure 9. There were a total of 4 targets, and each target location also acted as a starting position for the artifact. The artifact orientation varied with starting position, and it was always identical to the orientations that were used for targets at that location. There were 12 possible combinations of starting point / target pairings, and each was included in the experiment. The order of target / start position pairs was randomly determined. For each technique, participants carried out 4 trials per pairing, for a total of 48 trials per technique.

7.4 Procedure

Prior to the experiment, participants filled out a consent form and a pre-experiment questionnaire. A screening test was carried out

to determine whether they were able to reach each of the targets that were used in task 2. Each participant was then trained in using each of the four techniques. The experimenter explained each technique, and asked the participant to carry out 15 training trials. Each training session included ten trials from the precise task and five trials from the imprecise task.

For each task, the experimenter explained the steps, and instructed the participant to complete the trials as quickly as possible. After the task was completed using all techniques, the participant was given a questionnaire to assess their preferences and their perceptions of how fast and accurate they were with each technique.

7.5 Experiment Design

The study used a 4x2 repeated-measures factorial design. The factors were:

- Technique: TNT hand, block, hybrid; RNT
- Task type: precise or imprecise target

Participants carried out both tasks with all techniques. Technique order was balanced using a Latin square; tasks were always done in the same order: precise first, then imprecise. With 12 participants, 4 techniques, 2 tasks, and either 96 trials (precise) or 48 trials (imprecise) per task, the system recorded data for 6912 trials.

Completion time was measured from the appearance of the artifact until the object was successfully released in the target. Subjective data was also gathered, and participants ranked the techniques in terms of perceived accuracy, speed, and overall preference.

8 RESULTS

The overall mean completion time across all conditions was 3.81 seconds (standard deviation of 1.39 seconds). A 4x2 Analysis of Variance (ANOVA) showed main effects of both factors (technique type and task type). For technique type, $F_{3,33}=62.44$, $p<0.001$; for task type, $F_{1,11}=62.44$, $p<0.001$. As can be seen in Figure 12, TNT-Block was fastest, then TNT-Hand, TNT-Hybrid, and RNT. In addition, precise targeting was always slower than imprecise targeting.

There was also a significant interaction between technique type and task type ($F_{3,33}=62.44$, $p<0.001$). As can be seen in Figure 12, the difference between precise and imprecise targeting is larger for RNT than for the other techniques.

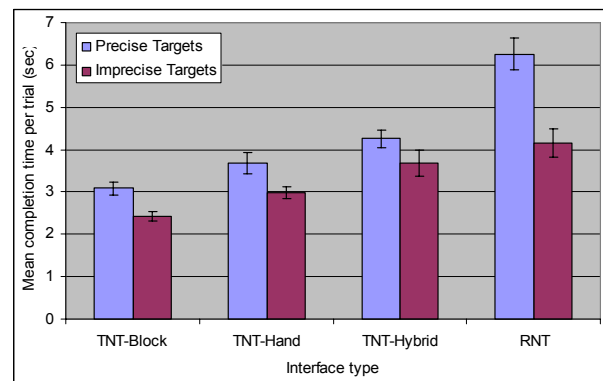


Figure 12. Mean completion times (error bars show one standard error).

A followup Tukey test was carried out to look for pairwise differences. We found that RNT was significantly slower than all the TNT techniques ($p<0.01$ for TNT-block and TNT-hand; $p<0.05$ for TNT-hybrid). Within TNT, the only difference was

that TNT-Hybrid was significantly slower than TNT-Block ($p < 0.05$).

8.1 Differences due to Rotation Angle

We tested the effects of different rotation angles (the minimum amount that the object had to be rotated from its starting position to the target). Due to different angles used in the two tasks, we analyzed the precise and imprecise tasks separately.

8.1.1 Angle Effects in Precise Tasks

We found a significant main effect of minimum angle ($F_{1,11} = 138.81$, $p < 0.001$); as can be seen from Figure 13, the smaller angle change (45 degrees) was always faster than the larger change (135 degrees). We also found a significant interaction between technique type and angle ($F_{3,33} = 18.39$, $p < 0.001$). More pronounced differences were seen for TNT-hand and TNT-hybrid than for TNT-block and RNT. As discussed below, this is likely due to the physical limits on wrist rotation that affect these two techniques, but not the others.

Follow-up t-tests showed that the difference between 45 and 135 degrees was significant for all four techniques ($p < 0.05$).

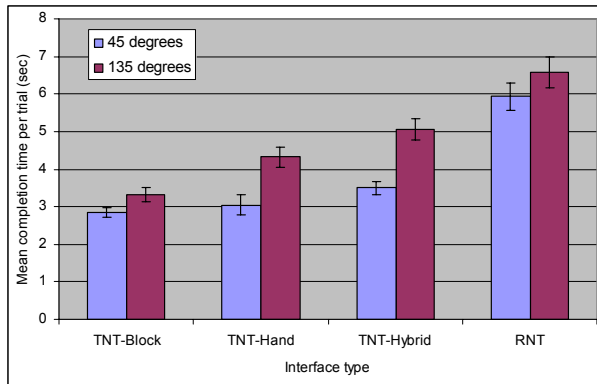


Figure 13. Mean completion time by technique and minimum rotation angle.

8.1.2 Angle Effects in Imprecise Tasks

In imprecise tasks, there was again a main effect of minimum angle ($F_{1,11} = 35.37$, $p < 0.001$). Overall, transfers of 180 degrees were about 0.4 seconds slower than transfers of 90 degrees (3.59 seconds vs. 3.16 seconds). There was no interaction between interface and angle for imprecise tasks.

8.2 Number of touches

The overall mean number of times that participants touched the artifact using the sensor during a trial was 1.61. There were significant main effects of interface ($F_{3,33} = 76.37$, $p < 0.001$) and of task ($F_{1,11} = 81.64$, $p < 0.001$). As can be seen from Figure 14, trials with TNT-block used the fewest touches, and those with RNT used the most. As expected, precise targeting used more touches in all techniques. There was also an interaction between number of touches and techniques ($F_{3,33} = 24.80$, $p < 0.001$); as shown in Figure 14, RNT has a larger difference between precise and imprecise tasks than do the TNT techniques. This may be due to the reduced rotational control that RNT provides, which makes precise targeting more difficult.

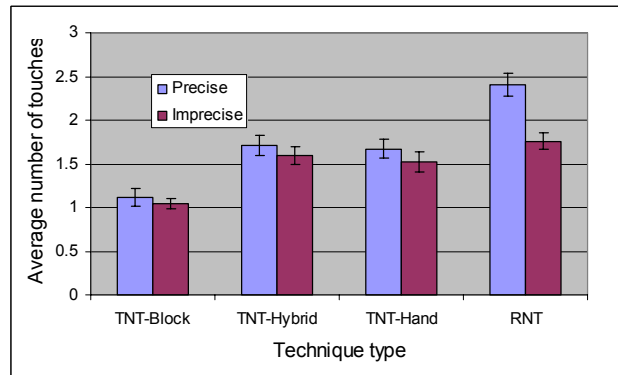


Figure 14. Mean number of touches by technique.

8.3 Subjective Findings

In questionnaires administered after each task, users were asked to rank each technique according to their perceived speed and accuracy, and according to their preference. Each was assigned a different number value for each category, with 1 being the best and 4 being the worst. Across all categories and in both tasks, users ranked the techniques in the same order. TNT-block was ranked highest, followed by TNT-hybrid, TNT-hand, and RNT. Figure 15 shows the mean values for the ranking that were given to each technique after the precise task. The participants assigned similar rankings to the techniques after the imprecise task.

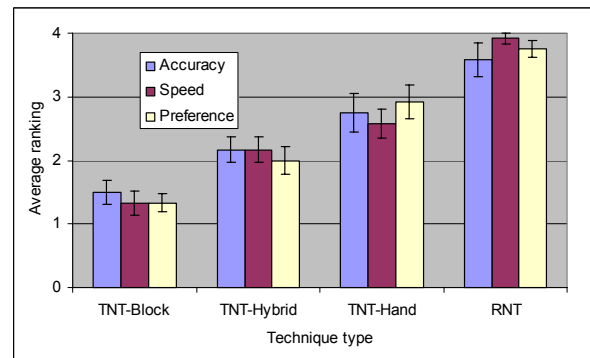


Figure 15. Mean subjective ranking for accuracy, speed, preference in task 1.

9 DISCUSSION

Our results indicate that performance measures and subjective data both show a similar trend. In all cases, TNT-block outperformed and was preferred over other techniques, and RNT had the lowest performance and preference scores. TNT-hand and TNT-hybrid ranked in the middle and had similar performance scores.

Participants had the best performance using TNT-block for both tasks, and they consistently rated it the highest in questionnaires. The differences in transfer times with large and small angles were relatively small, suggesting that TNT-block allows users to achieve large rotation angles without a significant time cost. Initially, we had hypothesized that this would be a useful technique for overcoming the range of motion limitations that are seen in TNT-hand, and this seems to be the case. Users were able to rotate the block in their fingers and, from informal observations, they seemed to be able to achieve rotation of up to 180 degrees in a single motion. In questionnaires, users described

the technique as “fast”, “easy”, and “accurate”, and they consistently gave it high scores on the ranking portion of the questionnaire. Since subjective and objective scores were consistent across both tasks, the technique may successfully generalize to a range of tabletop tasks.

TNT-hand and TNT-hybrid both had similar scores in trial times, but TNT-hybrid had higher subjective scores. Unlike RNT and TNT-block, participants’ completion times with these techniques increased significantly when transfer angles were large (135 degrees). This fits our initial observation that limitations in upper extremity range of motion, particularly in the wrist, could potentially impede performance in large angle rotation using the TNT-hand technique. This difference was seen in the TNT-hybrid technique as well, and this was somewhat surprising since we developed the hybrid technique to aid users in carrying out large angle rotations by adding RNT to the outer margins of the artifact. However, during the experiments, we often saw participants use the TNT-hand region exclusively for some trials, which may account for the similarity in performance scores with the TNT-hand technique.

RNT had the lowest performance scores and the lowest subjective ratings. On questionnaires, participants described RNT as “hard to use”, “complicated”, and “frustrating.” Completion times were significantly higher for RNT with the precise targeting tasks, but the task 2 trials, where the transfers spanned a larger distance and used a larger and more forgiving target, the transfer time dropped significantly and was much closer to that of the TNT techniques. Additionally, performance with RNT did not change significantly when comparing small angle transfers with large angle transfers. This suggests that RNT may be most useful in transfers where the required precision is low, and that users can use it without the performance costs that are seen in large area rotations with TNT-hand and TNT-hybrid.

We initially looked to real-world transfer techniques to inform the design of the TNT techniques. This approach allowed us to develop techniques that outperformed RNT in all experimental tasks, and users preferred them since they produced predictable results. For example, in questionnaires a participant indicated that TNT-block required “no physical/mental effort”, and another indicated that TNT-hybrid required “low physical and mental stress.”

In duplicating real-world motions in TNT-hand, we encountered range of motion limitations that interfered with efficiency in large rotation angles. Moving away from an input style that strictly duplicated the real world allowed us to overcome these limitations with TNT-block. While the TNT techniques outperformed RNT in all performance measures, the findings from TNT-block suggest that, in this case, designer intuition yielded a better solution than was possible through a strict duplication. Similarly, this suggests that our hypothesis, that naturalistic approaches would lead to better interaction techniques, was only partially correct.

Even though users showed better performance with TNT techniques, it should be noted that RNT was developed as a 2DOF technique. One of Kruger et al’s [2] stated goals was to develop a technique that could be used on common input devices (e.g. mouse, stylus), so it is unfair to conclude that our techniques are “better” since we operated under a different set of assumptions. The results show that when three degree of freedom sensors are available, and when sensor configurations can be developed that allow interaction that is similar to our techniques, the TNT techniques are preferable.

10 FUTURE DIRECTIONS

We have plans to investigate how the TNT techniques can be integrated with other tabletop interaction techniques. We are

interested in whether our techniques and sensor configurations can be adapted for general pointing and selection tasks. We also plan to investigate how TNT techniques can be integrated with other input devices including keyboards and styluses.

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