3D Marking Menu Selection with Freehand Gestures

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ABSTRACT

A controlled experiment was performed to evaluate the usability of freehand gestural target selection with different 3D marking menu layouts and target directions. We found that a rectangular layout was faster than an octagonal layout, with no significant increase in errors, and that our right-handed participants preferred to select to the right and forwards in a 3D marking menu. We propose an improved design for 3D marking menus based on our findings. The experimental results also suggest that designers should consider carefully whether or not findings from similar interaction techniques using hands-on devices can be carried over to the design of freehand gestural interaction.

KEYWORDS: Freehand gesture, 3D selection, marking menu.

INDEX TERMS: H.5.2 [Information interfaces and Presentation]: User Interfaces – Input devices and strategies, Interaction styles

1 INTRODUCTION

Increasing use of 3D displays, e.g. in cinemas, TV and computer games, has come at the same time as increasing use of gestural input, the latter currently seeing its most widespread use in games. The *combination* of these two rapidly developing technologies offers the potential for much richer and more natural user interaction and immersive experiences. We are therefore motivated to investigate potential user interaction techniques to work with the combination of 3D display and gestural input. The use of 3D displays raises questions on the design of 3D interface elements. Menu item selection is a common task in almost all applications so we focus on it in this paper as an example of 3D user interaction techniques.

3D menus can potentially map well to their associated 3D environments, giving a more immersive 3D user experience. Although considerable research has been conducted on menu selection techniques in 3D environments, most have used 2D menus and there are no well established 3D menu selection techniques.

Common approaches to tracking gestures include holding a motion sensing device (e.g. Wii remote), using fiducial markers that are tracked by a visual tracking system, or recognizing freehand movements using only a remote sensor (e.g. Microsoft Kinect) without on-body attachments or devices. As gestural interaction increases beyond the home gaming setting, freehand gestural interaction with displays that have no hands-on input device is likely to become even more important. But although the freehand gesture approach is often the most convenient because it does not require the user to hold or wear a device or to reach a touchscreen, it loses some benefits of such devices, such as the ability to take actions by clicking buttons or tapping surfaces.

The increasingly common and relatively inexpensive freehand tracking devices such as Microsoft Kinect may be less accurate than devices such as touch screen or mouse, so potentially requiring larger menu items and limiting menu item size and number. Since one advantage of freehand interaction is that gestures can be tracked in 3D, menus could be displayed and selected in 3D, which may help in presenting menus with more items without decreasing menu item size.

All of these factors encourage us to explore the design of 3D menus for freehand interaction in 3D environments. As there is no button clicking or touchscreen tapping available with freehand interaction, marking menus provide a potentially fruitful approach to freehand menu design because selection can readily be performed with marking menus solely by gesture, without clicking or tapping.

Hence, in this paper, we evaluate designs to support 3D selection using marking menus and freehand gesture. We report and compare various 3D marking menu layouts and selection gestures. An experimental evaluation is conducted to investigate different 3D marking menu layouts (variations on a rectangle and octagon) and different target directions. The results indicate that (i) Rectangle layout was faster than Octagon with no significant increase in errors, (ii) user performance was affected by different target directions, and users preferred to select to the right and front. Based on the experimental results and user feedback, we propose a conceptual design for an improved 3D marking menu called "Muffin".

2 RELATED WORK

2.1 Marking menus

Marking menus display their menu items around the center and menu selection is performed with a movement on or towards the target item. One purpose of a marking menu is increasing selection speed. Early work by Callahan et al [3] found pie menus reduce selection time and errors compared to linear menus. Kurtenbach and Buxton [13] also showed marking menus to be faster than linear menus.

Kurtenbach and Buxton [14] found that selection performance with hierarchical marking menus reduces when breadth increases to eight or more, or depth increases to two or more. Zhao and Balakrishnan [26] showed that a simple, i.e. single level, marking menu is more accurate than a hierarchical marking menu, the error increasing with the number of menu items and hierarchical depth, and that less physical input space for selection is need with a simple marking menu. They also found that for hierarchical marking menus, on-axis directions, e.g. North, South, East, and West, were more accurate than off-axis directions, while no such difference was found with a simple marking menu. Lepinski et al. [15] investigated marking menu selection on a multi-touch surface and indicated a significant angular error effect for gestures in different directions, for example, small angular error towards Down and large error to Right-Up.

Zone and polygon marking menus [25] used a tap action before the stroke, so both stroke position relative to tap location and

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stroke direction are used in selection, giving high selection speed and accuracy. When using pen devices with marking menus, the 3D orientation of the pen could also be used to aid pen tip selection [21]. Other devices can also be used to select marking menu items. Using a tilt technique [20], the user holds a mobile phone and selects with wrist movement. The menu was presented as a semi-circle in [20] and the user selected by rotating the wrist to the item angle. Results indicated that a non-linear menu layout with smaller menu items in the middle and bigger menu items on both sides had the best performance, suggesting that wrist movement accuracy varies with different wrist positions. Wrist and finger movements using a data glove can also be used together to select marking menus [18]. The user first tilts her wrist to select a subgroup with four menu items and then pinches her thumb to one of the other four fingers to select one item. Marking menu selection is also possible using a 6-dof magnetic tracker [19].

2.2 Gestural Selection

Considerable research has also been conducted on gestural selection. For example, to select occluded targets on a small touch screen, Yatani et al [24] rendered the overlapping icons with arrows pointing in a different direction for each object. The user put her thumb near the target on the screen and moved the thumb in the direction corresponding to the target. Directional gestures have also been used to perform menu selection for multi-touch displays [15].

Vogel and Balakrishnan [23] tested ray selection in 2D environments with gestures tracked using passive markers on the hand. They found that using finger direction to point was faster with large targets than with small targets but had high error rates. To address the absence of physical buttons, they used movement of the index finger and thumb as a "mouse-clicking" technique. However, the finger movements were too subtle to be tracked accurately by a motion camera without markers on the fingers. A time threshold has also been considered as an alternative to physical buttons [5] but it introduces a lag and so may slow down the selection and frustrate users.

2.3 Selection in 3D Environments

Ray-casting is a common selection approach in 3D environments, using a ray or spotlight to point and select [16]. An alternative to ray-casting is hand extension metaphor in which user's hand position is tracked in real space, typically using handheld devices or cameras, and hand position is used to control a cursor. In a densely populated environment, multiple objects may be in the ray selection range simultaneously. In this case, several techniques have been developed to disambiguate the target from other objects. For example, an effective extension of the ray selection technique is Depth Ray. The user controls a depth marker forward and backward along the ray to select a target intersected by the ray. Depth ray has performed better in dense 3D environments than related techniques such as point cursor and 3D bubble cursor [22].

Grossman and Balakrishnan [8] investigated pointing to a single target with the hand extension metaphor in 3D environments in respect of height, width, depth of the target and the movement angle. They found that moving forwards and backwards to select targets was significantly slower than moving left and right. They also found that target size dimension along the primary axis of movement have a greater impact on performance than the other two dimensions, and suggest that designers consider this when they try to reduce the amount of visual space occupied by 3D objects while facilitating selection.

2.4 Using Menus in 3D Environments

Kim et al. [11] classified menu selection systems for virtual environments according to different aspects such as 3D location, viewing direction, display items, and selection using 3D mouse or data glove. They found that selection performance is reduced if the menu is in a fixed location in the 3D environment. Menus have also been used in VR with different layouts and selection using a wired wand [6]. The results showed that a pie layout was 10% faster than vertical lists, and also confirmed that a fixed menu needed more time to select than a contextual menu.

Menu selection in 3D games was investigated in [4] using a Wii remote. Different menu types including linear, radial and rotary were compared. The results indicated radial menu was fastest with and without sub-menus and had fewest errors without sub-menus.

Tulip [2] used a 3D menu layout for a wired data glove, displaying the first three menu items on the first three fingers of the user's dominant hand and a "More" menu item on the little finger for triggering additional menu items that are then rendered on the palm. However, the results showed that this method is slower than using a tablet and pen for menu selection.

Kopper et al. introduced the SQUAD technique [12], using a marking menu to progressively refine selection after a sphere-casting initial selection. Results indicated that SQUAD was much more accurate than ray-casting, and was faster than ray-casting with small targets and in less cluttered environments.

In 3D environments, researchers have also used sphere shaped cues to display off-screen objects, such as mirror ball [17] and 3D arrow cluster [10]. These techniques can provide 3D location cues for the objects distributed around a 3D environment to support 3D interaction tasks such as navigation.

3 Design of 3D Marking Menu Selection

3.1 Design Challenges

Many marking menu selections in previous research were based on 2D displays with 2D pointing input devices. In this work, we extend the use of marking menus to 3D environments with 3D freehand gestural input. This brings several challenges in 3D marking menu representation and 3D freehand gestural selection.

First, the 3D marking menu items must be rendered carefully to make sure the user can see all the menu items and perceive their 3D locations correctly in order to select them.

Secondly, it can be challenging to select the target menu item from a 3D menu which may be densely populated by menu items, since each menu item may be surrounded in several directions by neighbouring menu items that act as distractors. Hence, in addition to facilitating perception of the correct location of each menu item, an effective 3D freehand gestural selection technique should facilitate effective selection of the correct menu item in the presence of such distractors.

Thirdly, as the menu items are distributed in three dimensions, hand movement in each direction (e.g. up, down, left, right, forward and backward) may be used to select corresponding menu items; which brings more challenges than moving on a 2D surface. Users need to coordinate their eyes and hands effectively to control their hand movement in physical 3D space and select the corresponding menu item in the virtual 3D space.

Finally, a menu selection typically contains three steps: triggering the menu to appear, selecting the target menu item, confirming the selection. Since freehand gestural interaction involves no button clicking or physical touch surface, a suitable design is needed for freehand gestural selection.

3.2 Gesture Design

Although ray-casting techniques have been shown to be effective for 3D selection, the origin of the ray is normally located in front of the objects. However, in a 3D marking menu, the ray origin is, by definition, located in the center of the objects, i.e. with the menu items arranged in three dimensions around it. Also, with ray selection using a device in the user's hand, it is easy to confirm the selection by clicking a button, but this is not available in freehand gestural interaction. Furthermore, as the hand position is virtually surrounded by menu items in all three dimensions, there is no extra dimension and very limited space available for an additional confirmation gesture following the selection gesture. For these reasons, we designed our freehand gestural 3D marking menu selection technique based on the hand extension metaphor rather than ray-casting.

For freehand gesture interaction without holding or wearing a device or fiducial marker, we can fairly easily track major joints such as hand, elbow or shoulder, however, small movements like wrist rotation or finger movement are difficult to track precisely. Given our requirement for reasonably low cost technology that can perform well in potentially visually noisy environments, small movements of the finger or wrist are not suitable for current freehand tracking technology. Hence, we prefer to use the acceleration or movement of the hand, or the angle from hand to elbow or shoulder for tracking the freehand gestures.

After a selection gesture, another action is typically required to confirm the selection with marking menus, such as button clicking [20, 12], pen down/lift [25] or finger movement [18]. In freehand gestural interaction, there is no handheld device or touch surface. Escape [24] and cross selection [1] have shown that it is possible to perform gestural selection without an explicit confirmation action. Drawing on this research, we designed two marking menu selection techniques to enable selection and confirmation with a single directional gesture.

The direction of finger movement is used to select the target in Escape [24]. We applied the same strategy to freehand gesture selection (Figure 1a). The user moves her hand in the appropriate direction, the direction is detected, and the menu item in the corresponding direction is selected. Given that freehand motion tracked by a low-cost camera may be noisy and less accurate than pointing on a touch screen, we added a speed requirement: the direction is detected only when the hand movement speed is faster than a threshold. We call this technique Stroke.

Our second technique is based on the cross selection technique [1]. In cross selection, the target is selected simply by moving the cursor across a boundary without a button click or similar confirmation. This technique could also be used in a 3D environment where the user selects the target by moving the cursor through a corresponding plane, as shown in Figure 1b. We call this technique Reach.

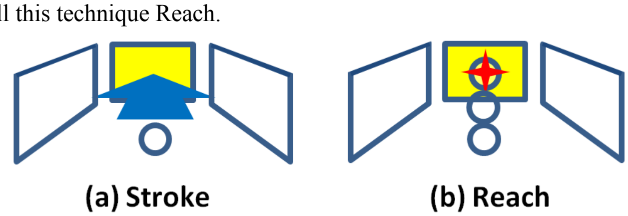

Figure 1. Selecting an item using gesture (Top-Front view). (a) Stroke, using the movement's direction to select. (b) Reach, using the cursor position to select; which must go through target plane.

Marking menus are usually invoked by a mouse click or pen touch, however, these inputs are not available in freehand gestural interaction, so we need to find a way to invoke the marking menu. Again, as the marking menu items may be distributed in all dimensions, movement of a single hand may not be suitable because it is easy to confuse the trigger gesture with a selection gesture. One benefit of motion tracking without fiducial markers is that the tracking is not limited to the marked body parts; in contrast, it can track the movements of the whole body. This enables using movement of other body parts as the menu trigger gesture. Here, we used a "hands up" gesture performed by the user's other hand as the menu trigger gesture.

3.3 Display Design

We chose the number of menu items for freehand selection based on previous work with 2D marking menus. With pie cursor [7], four and eight items were tested, and Escape [24] used 8 directions for its icon arrows. More items have been tried in [26], and results showed slower selection time and higher error rates for more than eight menu items. Zhao et al. [25] also conclude that to maintain acceptable accuracy rates, marking menus should not exceed 8 items.

Given that the movement ranges of a thumb [24], mouse [7], or handheld tracking device [8] are smaller than an arm, the radius of the marking menu and distance between each menu item could be larger with our freehand gestural selection. This makes our marking menu potentially able to handle more menu items.

Taking all these constraints into account, we constructed the 3D marking menu by putting 8 marking menu items in the vertical plane centred on the initial cursor position, 3 items in the front and another 3 behind the cursor position. These 6 items were in the same horizontal plane. So, we had 14 menu items in total.

Grossman and Balakrishnan [8] suggested that target size dimension along the main selection direction has a greater effect on performance than in the other two dimensions, however, this conclusion is based on the "move and click" selection technique using a 6-dof tracker equipped with a button. In our selection technique for freehand gestural selection (Figure 1), users only need to move their hand toward the target direction (with Stroke) or pass through the target plane (with Reach). Thus, all menu items in our 3D marking menu were 2D rectangles, so their size along the main selection direction approximated to zero.

Various types of presentation have been used for marking menus in 2D, such as pie [7], radius zone [9], rectangular zone and polygon [25]. We found polygon to be a good presentation to facilitate both Stroke and Reach. For a polygonal 2D marking menu, each menu item is a line occupying some length. If these items were selected by freehand gesture, we could consider the depth of the items as infinite. But for a 3D marking menu, since there are items in front and behind, the depth of the menu items in the horizontal plane cannot be infinite. Thus, rather than a line in a 2D plane, each such menu item is represented as a vertical rectangle at a given position in 3D space (see Figure 2).

In pilot trials, we found that if we render all the menu items as rectangles, their visual representations are similar and the user will have difficulty in perceiving the item's location in the 3D environment. So we rendered only the 6 menu items in the front and back as rectangles, and rendered the other 8 menu items (in the vertical plane centred on the cursor position) as lines in order to provide visual separation; but the effective selection areas for all menu items were still rectangles.

Considering that the range of human hand reach both from Up to Down and from Right to Left is almost the same (about 2 arms' length), we used an octagon as the layout of the menu items in the vertical plane centred on the cursor position, with each item having the same distance to the center. We could also apply the same layout for items in the front and back, giving the first layout design (Figure 2a, Octagon).

However, hand movement range forward and backward is shorter (about 1 arm's length without body movement). To accommodate this difference, we also tested a rectangular layout for the items in front and back (Figure 2b, Rectangle).

Considering that the arm movements forward and backward are not symmetrical, e.g. there is more space when the arm is moving forward, while the hand is obstructed by the upper body when moving backward, we also evaluated non-symmetrical layouts, i.e. the combination of octagon in front and rectangle behind (Figure 2c, Octagon/Rectangle), and rectangle in front and octagon behind (Figure 2d, Rectangle/Octagon). For all four conditions, the 8 menu items in the perpendicular plane centred on the cursor were in the same locations. The 3D marking menu names reflect the layout of the menu items in the front and back.

In an initial study, we found that the Stroke technique produced a lot of errors in 3D marking menu selection. This is probably because the difference in direction between 14 menu items is too slight for the hand to separate them effectively. So we carried forward only the Reach technique for investigation in the experimental evaluation reported in the following section.

Given that moving forwards and backwards to select targets is significantly slower than moving left and right [8], and the relatively short range of forward and backward hand movement, we tried to reduce the Z-depth of the 8 menu items located vertically, so that the 6 items in the front and back could be closer and therefore easier to reach. However, we found that selection errors for the 8 vertical items increase quickly when their depth becomes smaller than their length. So we maintained the selection area of these 8 items as square in the following study.

4 EXPERIMENTAL EVALUATION

We conducted a controlled experimental evaluation to investigate the effect of different 3D marking menu layouts and target directions using freehand gestural selection. The independent variables were 3D marking menu layout (Octagon, Rectangle, Octagon/Rectangle, Rectangle/Octagon, as shown in Figure 2) and TargetDirection (Up, Down, Left, Right, Front, Back, Left-Up, Right-Up, Left-Down, Right-Down, Left-Front, Right-Front, Left-Back, Right-Back). We recruited twelve volunteers (nine male and three female), between 22 and 30 years of age with a mean age of 25.58 (sd = 2.15). All of them are postgraduate students. All participants were right-handed and had experience of stereoscopic 3D displays, such as watching 3D movies, and experience of gestural interaction, e.g. using a Wii remote or Microsoft Kinect for playing games.

4.1 Procedure

There were 4 sessions, one for each 3D marking menu layout. The order of the sessions was randomized. In each session, there was a practice block of 52 trials (3 trials in each direction), followed by another 2 test blocks with 52 trials each.

Each trial started with a "hands up" gesture with the left hand. When the gesture was performed, a 3D marking menu appeared with the target menu item highlighted in yellow. The user's hand position was represented as a yellow sphere (diameter 5 cm in virtual 3D space) in the center of the marking menu. This cursor continuously followed the user's right hand movement.

The 8 vertical menu items were 80 cm from the center of the marking menu in virtual 3D space, and their width was 66 cm (the orange lines in Figure 2). Although they were rendered as lines for visual separation from other items in front and behind, their effective selection depth was 66 cm, so all the menu items located vertically were squares in motor space. In the different 3D marking menu layouts, the size and distance of the menu items located vertically were the same, while the size and distance to the center of horizontal items differed as a feature of the layout. In the Octagon menu layout (Figure 2a), the other 6 menu items located at the front and back were squares of the same size (66 cm x 66 cm). The menu in Rectangle layout (Figure 2b) were rectangles sized 66cm x 53 cm. In the other hybrid layouts (Figure 2c, 2d), their size was the same as the corresponding menu item in the Octagon or Rectangle layout. All the menu items in the front were rendered as translucent in order to show the other, occluded, menu items.

User movement was mapped from real space to the visual 3D space as 0.3:1 (when the user's hand moved 3 mm in real space, the cursor moved 1 cm in virtual 3D space). A selected menu item disappeared when a selection was detected. If the user selected an item other than the target, an error sound was played. If the target was selected, the user was instructed by text on the display and an audible beep to start the next trial.

After the whole test was finished, the participant answered a questionnaire on marking menu layout and target direction preferences. They were asked to rate their preference for the different layouts and target directions from 1 (strongly dislike) to 10 (strongly like), and provide comments about their preferences. The whole study took about 45 minutes per participant.

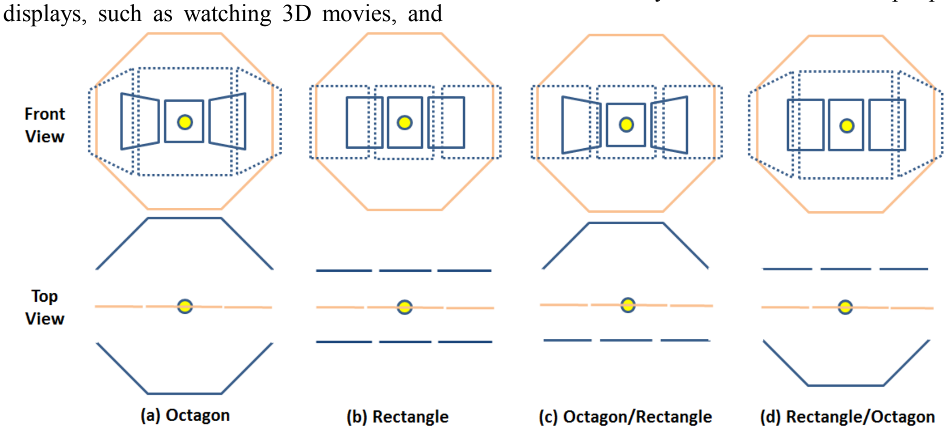

Figure 2. 3D marking menu display design. In the front view, the rectangles drawn in dotted blue lines represent the menu items at the back (i.e. closer to the reader), the rectangles in solid blue lines represent the items in front, and the orange lines represent the menu items located in the vertical plane around the initial cursor position. In the top view, the blue lines represent items in front and back, and the orange lines represent items located vertically. The yellow sphere in the center represents the initial cursor position.

4.2 Equipment and Setting

The 3D environment was displayed on a Samsung PS50C680 50" 3D plasma TV with 120 Hz refresh rate at 1280 x 720 resolution. Samsung SSG-2100AB/XL 3D active glasses were used by participants to view the display in stereoscopic 3D. The height from the ground to the center of the display was 107 cm, and the user stood 200 cm in front of the monitor. The user's hand movements were tracked using a Microsoft Kinect camera, with a refresh rate of 30 fps, and the OpenNI API on Windows 7. The Kinect camera was placed on top of the display. The experiment setting is shown in Figure 3.

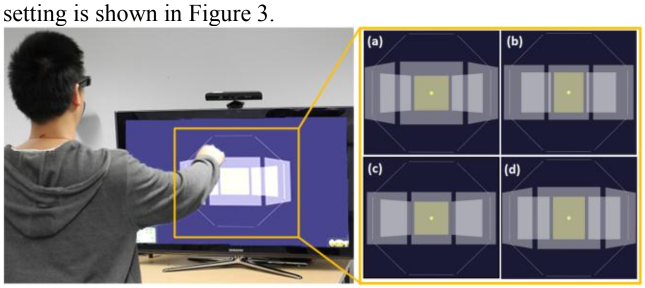

Figure 3. Experimental setting and snapshots of the 3D marking menus with menu item in front as a target. (a) Octagon (b) Rectangle (c) Octagon/Rectangle (d) Rectangle/Octagon.

4.3 Results

4.3.1 Selection Time

A repeated-measures ANOVA for 3D marking menu layout x TargetDirection was used to analyze the results. Main effects were found for 3D marking menu layout ($F_{3,33}$=5.00, p=.006) and TargetDirection ($F_{13,143}$=7.47, p<.001). An interaction effect was found for 3D marking menu layout x TargetDirection ($F_{39,419}$=2.58, p<.001). Mean selection time for Octagon was 1.31 s, for Rectangle was 1.13 s, for Octagon/Rectangle was 1.21 s, and for Rectangle/Octagon was 1.20 s.

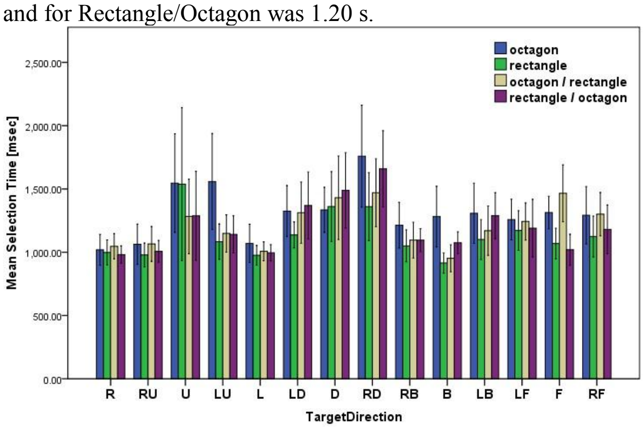

Figure 4. Selection time for marking menu layout x TargetDirection.

Post hoc Bonferroni pairwise comparisons showed that Rectangle was significantly faster than Octagon (p=.022). Mean selection times across the conditions are shown in Figure 4.

Further analyses using one-way repeated-measures ANOVA for TargetDirection in the four different marking menu layouts were performed. As illustrated in Figure 5, with Octagon each of Right and Right-Up was significantly faster than all of Front and Right-Down. With Rectangle, Left was significantly faster than Left-Down. With Octagon/Rectangle, each of Left and Back was significantly faster than Up, and with Rectangle/Octagon, each of Right, Left, Front, Right-Up, and Right-Front was significantly faster than Right-Down (p<.05 or more significant for all pairs).

In Figure 5, directions represent in blue arrows are significantly faster the directions in green arrows with each layout.

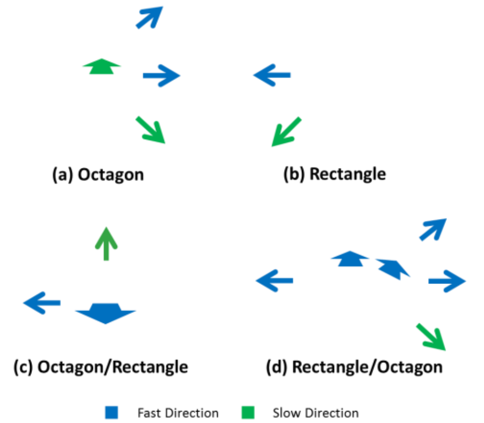

Figure 5. Selection time comparison in different directions. Blue directions took significantly less time than green directions (p<.05). Line arrows represent directions in the vertical plane, and block arrows represent directions in the horizontal plane.

We also compared the selection time in the on-axis and off-axis directions. A two-tailed dependent T-test found no significant difference (t_{11}=-1.51, p=.16).

4.3.2 Error Rate

Users were required to select the target successfully, if necessary trying more than once. Each failure to select the correct target was recorded as an error. The first erroneous direction when users failed to select the target menu item was also recorded as "error direction" for this "target direction". A repeated-measures ANOVA was used for 3D marking menu layout x TargetDirection, as shown in Figure 6.

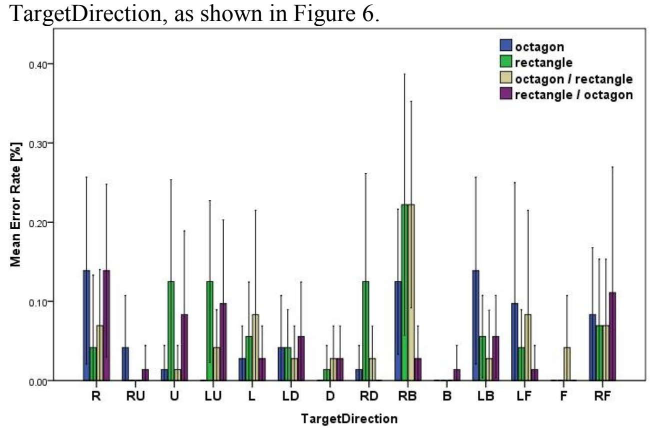

Figure 6. Error rates for 3D marking menu layout x TargetDirection.

We found main effects for TargetDirection ($F_{13,143}$=3.02, p<.001), but no significant effect was found for menu layout ($F_{3,33}$=0.77, p=.52). We also found an interaction effect for 3D marking menu layout x TargetDirection ($F_{39,429}$=2.12, p<.001). Mean error rate for Octagon was 5.26%, for Rectangle was 6.94%, for Octagon/Rectangle was 5.55%, and for Rectangle/Octagon was 5.06%.

Follow previous marking menu research [4], we also analysed errors in on-axis directions, i.e. Right, Down, Up, Left, Front, Back, and off-axis directions (Figure 7). A two-tailed dependent T-test found that whether the direction was on-axis or off-axis had no significant effect on error rate (t_{11}=-2.04, p=.07).

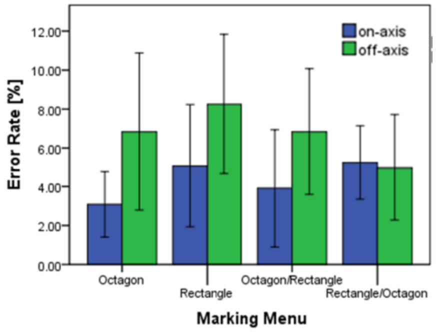

Figure 7. Error rates for on-axis and off-axis TargetDirection and 3D marking menu layout

The distribution of error directions is illustrated in Figure 8. The top 4 mistakes in each 3D marking menu layout are shown. The user's hand moved to Back very easily when trying to select Right-Back (a, b, c), and to Right-Back easily when the target was to the Right and the Octagon layout was used at the back (a, d). In the second and third rows of (b, d), we find that the user's hand moved to Front easily when selecting Up, and moved to Left-Front easily when selecting Left-Up if the Rectangle layout was used at the front. The user also moved her hand easily to Left when trying to select Left-Back and Left-Front in the Octagon layout (a, third and fourth rows). Overall, forward and backward directions produced most of the errors shown in Figure 8, backward producing more than forward.

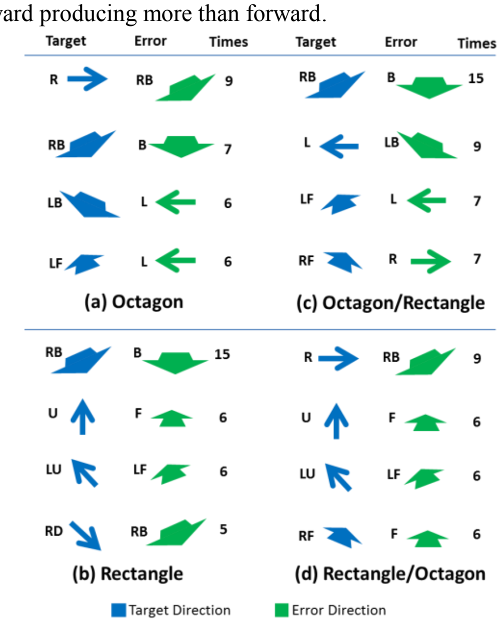

Figure 8. The first direction selected by mistake (green arrows) when the user tried to select the target direction (blue arrows). Line arrows represent directions in the vertical plane, and block arrows represent directions in the horizontal plane.

4.3.3 User Preference

User preference data on the 3D marking menu layouts and target directions were collected by questionnaire. Figure 9 shows user preferences for the 3D marking menu layouts. A one-way repeated-measures ANOVA for menu layout found no effect ($F_{3,33}$=.33, p=.801). Although there is no generally preferred 3D marking menu layout for all participants, some participants showed strong personal preference for certain layouts. With respect to visual feedback, some participants preferred the combinations of Octagon and Rectangle because they provided visual differences between the items in front and behind and facilitated their identification of item position. However, some other participants preferred the Octagon layout because it represented the depth difference of items in front and behind more clearly, and the symmetrical shape made them feel comfortable. The visual feedback in the Rectangle layout was disliked by users because the items in front and behind looked similar, however, some participants preferred Rectangle because the items in front and behind are all in the same plane, so it was easier for them to locate and select the items by right angled hand movements, e.g. moving the hand a little to the right and then forward to select Right-Front, rather than making a diagonal movement.

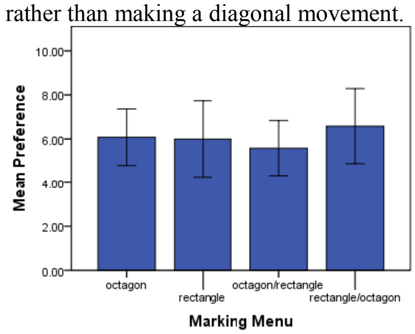

Figure 9. User preference of marking menu layout.

Some participants also commented that they preferred the Octagon layout when it appeared in the back, because it is not easy to control the hand moving backward, and the Octagon layout gave each item more space, making it easier to select. They even suggested putting only one item at the back and removing the Left-Back and Right-Back options. This comment aligns with the error analysis in Figure 8. Participants felt that selecting forwards was more accurate than backwards, although it required a little more effort.

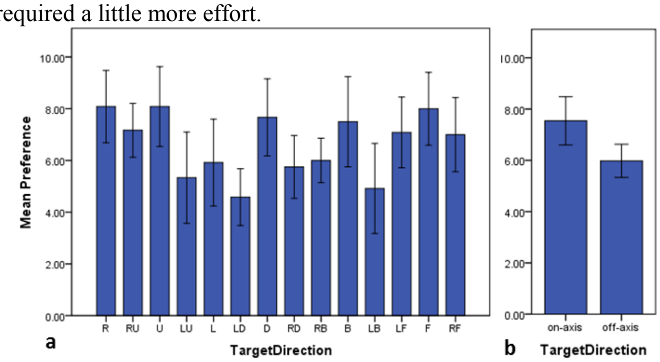

Figure 10. User preferences for (a) all TargetDirections and for (b) on-axis and off-axis TargetDirections

Figure 10 shows user preferences for (a) all TargetDirections and (b) on-axis and off-axis TargetDirections. A one-way repeated-measures ANOVA found a main effect for TargetDirection ($F_{13,143}$=4.18, p<.001): Right and Front were the preferred target directions, while participants disliked Left-Down and Left-Back. They commented that because they selected using their right hand, it was comfortable to move the hand to the right. It was also comfortable moving the hand forward. In contrast, when moving the hand to Left-Down and Left-Back, the hand had to move across the body close to the chest, making them feel uncomfortable.

A two-tailed dependent T-test found significantly higher preference for on-axis directions than for off-axis directions

(t_{11}=4.77, p<.001), as shown in Figure 10(b). Users commented that when they see an on-axis target, they perceive the direction and start to move the hand in that direction easily and confidently, while for off-axis directions they needed to hesitate to think about the direction and moved the hand more carefully. In other words, the off-axis directions probably required more mental and physical workload than the on-axis directions in our 3D marking menu.

Users also made some other suggestions about the visual feedback of the cursor. They said it was not easy to select if they did not know the relative location of the cursor and the 3D menu items, and the stereo 3D display did not provide enough clues about this relative location. So it would be better if the cursor projections on each dimension could be displayed on related menu items, so the user has a clear perception of the current cursor position relative to the menu items in the 3D environment.

4.4 Discussion

The Rectangle layout was significantly faster than the Octagon layout, while there were no significant differences in error rates between them. The different layouts of Rectangle and Octagon make the Rectangle menu items located in the horizontal plane smaller in size but closer to the menu center than with Octagon (Figure 2). The results suggest that these differences made the Rectangle layout faster than Octagon using freehand gesture without significantly sacrificing accuracy. However, although the error rate of Rectangle was not significantly different, we found that the smaller space of the Rectangle layout tended to produce more errors in the forward and backward directions (Figure 8b, 8c, 8d). Users also noted that the menu items in front and behind of Rectangle looked similar, affecting the perception of their 3D location. These findings suggest Rectangle still needs to be improved.

Significant effects of target direction were found on both selection time and error rate. Directions towards Right and Front were comfortable for our right-handed participants and on-axis directions such as Up, Down and Back were also preferred; users did not like Left-Down and Left-Back. So we could consider using only on-axis directions if higher accuracy or fewer options are required. When there are many options, we could put high priority or commonly selected options in the on-axis directions.

We also found that users had difficulty selecting the targets located vertically, especially downwards (Down, Left-Down, Right-Down). This may be caused by the arm movement pattern: the hand usually does not move in the same perpendicular plane as the user's chest. For example, when the hand moves to Right-Down, it also moves back at the same time. Although people can try to adjust their action for moving their hands in a vertical plane, such as involving more elbow movement, it increases the physical demands of the arm movements and requires users to pay more attention to their hand location. This suggests that the layout of items in the vertical plane could also be improved.

Compared to other marking menu selection techniques, such as using fingers on a touch screen [15, 24], we found freehand gestural selection has both similar and contrasting characteristics regarding target directions. For example, in Escape users disliked Left-Up, Left and Left-Down [24], similar to our results. However, no significant effect of target direction was found for time or error rate in Escape [24], and the stroke angular error is small towards Down while big towards Right-up on multi-touch surface [15], in contrast to our results. A lesson is that such differences should be considered by designers of freehand gestural interaction and that designers should consider carefully whether or not findings from other gestural interaction techniques that involve handheld devices can directly be carried over to the design of freehand gestural interaction.

Our study suggests that our design of 3D marking menus could be improved. Based on the experimental results and user comments, we propose an improved 3D marking menu layout. Figure 11 shows the concept design in motor space. For the menu items in the front, we begin with the design of Rectangle (Figure 1b), and to reduce the errors (see Figure 8b, 8d), we add a curve (less than Octagon for shorter movement distance). For the menu items at the back, we propose reducing the number of menu items to one. This reduction also provides more space to adjust the placement of the items in the vertical plane centred on the cursor position. As we found, when a user selects these items, her hand also moves back at the same time. So we propose placing these items to follow the natural hand movement (solid orange lines in Figure 11), extending towards the position of the user's elbow. This 3D marking menu layout looks like a big muffin with the bottom towards user's chest, so we refer to this 3D marking menu design as "Muffin".

As we found the hand is very accurate moving forwards, it could be possible to add another two items in the Front-Up and Front-Down positions, so having 5 items in the front. But we do not suggest increasing this number to more than 5 in the front because it could be hard for the user to perceive the menu item locations and perform the corresponding selection gestures.

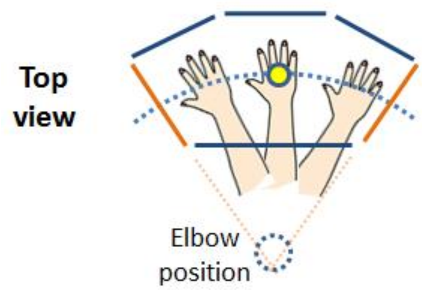

Figure 11. Concept design for "Muffin" 3D marking menu (Top view of the middle horizontal cross-section). The blue lines represent items in front and behind, the orange lines are items located in the vertical plane centred on the initial cursor position. The yellow sphere is the initial cursor position.

5 LIMITATIONS AND CONCLUSION

Most previous research on gestural interaction has used fiducial markers or handheld devices for motion tracking, however, in many scenarios users cannot be expected to carry a specific handheld device, data glove or fiducial markers around. Our target is to enable hands free interaction without holding, wearing or attaching anything on the human body. The user's body alone can be an effective input device, enabling flexible interactions.

We have designed, implemented and evaluated freehand gestural selection using a 3D marking menu. We proposed 3D marking menu layout designs and gestural selection techniques, and conducted a controlled experimental evaluation investigating the effect of 3D marking menu layouts and target directions in menu selection task. The results showed that freehand directional selection for a 3D marking menu was affected by both factors.

In our study, we evaluated only right-handed participants selecting with their dominant hand. While it is possible the results are bilaterally symmetrical for left-handed people, we had no evidence from this study. We tested selection with simple marking menus of 14 items. The effects of number of menu items and menu hierarchical depth are still not clear. Menu radius and cursor movement ratio were constant in our study too. Variations in these parameters may or may not also affect selection performance.

Freehand gestural selection is a potentially valuable technique enabling flexible and free interaction 3D environments, without any requirement for specialist devices to be worn on or carried by the user. Marking menus are a potentially useful interaction mechanism for use with freehand gestures. Our findings suggest that while the design of freehand gestural interaction using such mechanisms can leverage findings from more established interaction techniques such as mice and touchscreens, it would be dangerous to rely on such findings as applicable to freehand gestural interaction without further evaluation. The design space, and the number of potential variables and experimental conditions to be explored, is huge. Future work could tackle some of these factors, including comparing the performance of 3D and 2D marking menus and exploring the effects of other 3D menu layouts.

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