Empirical Evaluation of Gaze-enhanced Menus in Virtual Reality

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ABSTRACT

Many user interfaces involve attention shifts between primary and secondary tasks, e.g., when changing a mode in a menu, which detracts the user from their main task. In this work, we investigate how eye gaze input affords exploiting the attention shifts to enhance the interaction with handheld menus. We assess three techniques for menu selection: dwell time, gaze button, and cursor. Each represents a different multimodal balance between gaze and manual input. We present a user study that compares the techniques against two manual baselines (dunk brush, pointer) in a compound colour selection and line drawing task. We show that user performance with the gaze techniques is comparable to pointer-based menu selection, with less physical effort. Furthermore, we provide an analysis of the trade-off as each technique strives for a unique balance between temporal, manual, and visual interaction properties. Our research points to new opportunities for integrating multimodal gaze in menus and bimanual interfaces in 3D environments.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**; **Virtual reality**; **Mixed / augmented reality**.

KEYWORDS

Gaze, Manual input, Virtual Reality, Design, Menu, Pointing

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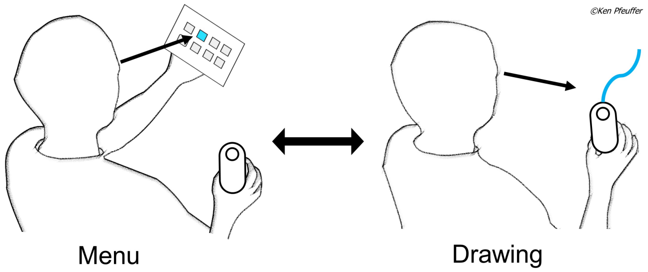

Figure 1: In many UIs, the user's visual attention shifts between main task and menu. We investigate how gaze input of the shifts can be exploited to enhance menu interaction.

1 INTRODUCTION

Menus are an essential part of the user interface (UI). They are commonly used in many scenarios, to look up modes and change states of the application, such as UI settings, colours for a pen, or tabs in a browser. In Virtual Reality (VR), an interesting case is the bimanual UI where one hand manipulates a virtual pen to draw, and the other hand holds a menu [1]; naturally like an artist holding a brush and a colour-palette – yet with new digital features, such as ray pointing and 3D drawing.

Changing a mode in a menu means for users that they shift their attention between the main task of the design work, and a secondary task of changing modes to customize the virtual application experience. Such round-trips to menus can become quite costly with increasing frequency of use and distance travelled, and it has been argued that interfaces and techniques should be designed to render them effortless and avoid detracting the user from the main task [23]. This is quite intricate however, with multiple involved substeps from focusing on the menu, finding the desired mode, selecting it, and moving back to the point in space where the line should be drawn to then continue drawing.

This research focuses on understanding and improving such context switching processes for menus by using eye tracking, an increasingly supported input technology on head-mounted displays. It estimates the user's point of focus (gaze), revealing what the user is visually attending to, such as when the user shifts from a drawing context to the menu context (Figure 1). As gaze movement to a target precedes manual movement, in principle, this information

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can be exploited to make mode-switching easier and thus reduce the cost of secondary menu task interaction. Cost can be the time needed to perform the action, the mental load involved in switching and finding the item, or the physical exertion exhibited in hand and arm movement. Prior work has investigated mode-switching on the example use cases of drawing and design [26, 46, 47], however these works usually focus on a single and temporal mode-switch, while we regard the case of users switching between multiple, persistent modes to represent the nature of menus.

We investigate gaze interaction techniques to facilitate users in their interaction with menus in VR. Gaze input was extensively studied in VR, showing promising results for fast target selection with low physical effort [3, 16, 24]. For instance, a basic eyes-only approach is dwell time, where users look at the target for a specific time. This leads to fast selections, however is subject to the Midas Touch problem where it is ambiguous whether a gaze is intended to select or simply look [22]. To account for this issue, researchers proposed gaze with manual confirmation, which is plausible in the context of VR drawing with controllers. Such multimodal techniques often adhere to trade-offs between the involved modalities, such as temporal performance vs. error rate or physical effort vs. eye fatigue. It is important to understand factors of user performance and experience that affect such techniques, to make an informed decision in the design of future UI integrating them.

In this paper, we present a user study that compares multimodal gaze and manual input techniques for virtual menus. The baselines are instances of direct (controller) and indirect (raypointing) selection. Our main research question is: *how do different variations of multimodal gaze and manual interaction techniques affect the user's performance in a VR menu-selection task?*. The investigated techniques provide a range from completely manual (controller pointing), to eyes-only input (dwell time). We describe the interaction design in detail in our concept section. The techniques are studied in a common task of switching colour modes as a secondary task, then draw lines as the primary task. We provide an extensive analysis of the study results, including performance, physical movement, coordination, and user feedback.

The findings indicate that a direct approach of a dunk brush metaphor is performance-wise one of the fastest, but trades off with higher need of physical demand. Dwell time, in contrast, has no physical effort and can be similarly fast at the expense of eye-fatigue, as reported by users. The indirect methods trade several of these factors to form unique techniques; for example, the manual-only raypointing method leads to additional movements and wrist rotation, which the multimodal techniques avoid with the integration of eye movements. Our study extends the prior knowledge by categorising and quantifying these and more characteristics of interaction techniques in the realm of multimodal gaze and manual input, useful to inform future gaze based UI.

Contribution Statement. Our contributions include (1) a report on the design of multimodal gaze-based interaction techniques that are integrated in bimanual drawing and menu tasks, (2) provision of a user study that compares these techniques against two common baselines, dunk brush and pointer, and (3) analysis of quantitative and qualitative experimental data, exploring the effects of the techniques regarding performance and experience.

2 BACKGROUND AND RELATED WORK

Our work builds on gaze interaction techniques that we review in general, and then specifically for VR. We then discuss prior work on menu interfaces and mode switching studies in VR.

2.1 Gaze Interaction

Eye gaze has been long established in HCI research [19, 22]. As input device, eye gaze has been shown to be faster than manual input and requiring no acquisition time [43]. A major challenge of gaze is the Midas Touch problem, for a system to be able to disambiguate whether an eye fixation is only 'looking' or an intended command [22]. As an approach, the dwell time technique employs a time threshold to account for this. However, it is still prone to accidental activation when staring for longer without intention.

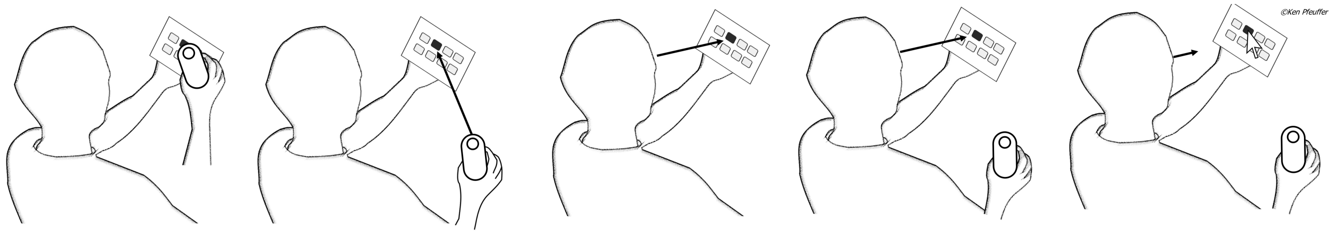
As another research direction to approach disambiguity, researchers have proposed gaze in combination with manual input. The investigated combinations range from early work on gaze and controller [4] as well as button input [22], to mouse [11, 20], multi-touch [32, 45], mid-air gestures [8, 39], feet [15], or smartwatch [13] input. Each modality adds their own individual characteristics, providing unique interaction possibilities in combination with gaze.

2.2 Gaze Interaction in VR

Gaze is increasingly investigated for VR with advances in spatial tracking technology, with applications for eye-hand coordination [31], face-to-face communication [42], or biometrics [34]. Early work on input from Tanriverdi et al. [48] and Cournia et al. [9] compared gaze and conventional pointing. Although this evaluation did not show an obvious speed advantage, gaze interaction was still found to be beneficial in many tasks. Zeleznik et al. [50] and Poupyrev et al. [40] introduced areas where gaze can be helpful, e.g., gaze as an additional hand which can expand common hand interactions with extra parameters or multitasking when the hands are occupied with other objects.

Various studies investigated gaze based interaction for selection tasks in VR. Qian and Teather found gaze to be superior to head pointing in their task [41] while Blattgerste et al. and Luro and Sundstedt found gaze to be faster and less effort than head pointing [3, 27]. Piumsomboon et al. explored variations of gaze and head based selection techniques in virtual environments [38]. A study demonstrated that each technique has their strength and weaknesses. Esteves et al. present a study comparing selection techniques for head based pointing [12], finding that handsfree (dwell time) and hands-on (using manual input) are most promising.

Others investigated interactive capabilities, such as Pfeuffer et al.'s Gaze & Pinch interaction technique [36]. Objects can be selected via gaze and manipulated through uni-manual and bi-manual freehand gestures. However, they do not provide an empirical study on their methods. *Eye See Through* [29] combines eye tracking in VR with the 'see through interface', introduced earlier by Bier et al. [2] for two-dimensional displays. Here, the user looks through a transparent menu at the target and can trigger the controller button for selection. Sidenmark and Gellersen provide synergetic interaction through the combination of gaze and head movements [44]. Hirzle et al. presented a design space for gaze interaction on head-mounted displays, with a focus on human and technological aspects



a) Dunk Brush b) Pointer c) Dwell-time d) Gaze Button e) Cursor

Figure 2: Investigated interaction techniques: Dunk Brush (a) and Pointer (b) are two commonly used manual, but contrasting techniques. Dwell time (c) allows eyes-only selection of targets. Gaze Button (d) strives a trade-off with gaze selection and manual controller confirmation. Lastly, in Cursor (e) gaze only indicates attention to menu, where users interact with a cursor manipulated via controller.

that need to be considered for interaction design [18]. Our work extends the prior art, by focusing on the menu interaction context.

Kyto et al.'s study resembles a close match to our work [24]. In their study, multimodal techniques using gaze, head, and manual input devices are assessed in Augmented Reality environments. Their study focuses on the time/error trade-off, and finds gaze only to be the fastest, but also the most error prone. Our work is complementary, covering a bimanual menu task, takes a deeper look at the trade-offs of different multimodal techniques regarding their performance, physical and eye fatigue, and considers the current status quo VR interactions of controller pointing.

2.3 Menu and Mode Switching Research in VR

Menus can be on a fixed position, be activated by a button, kept in the user's field of view or be fixed to the user's body [30]. The advantages of binding them to the user's body are that the menu is easy to find and does neither disturb the view nor occupy a physical button on the input device [30]. Dachselt et al. provide a survey and classification of menu UIs for VR [10]. Surale et al. evaluated mode switching of free hand gestures in two experiments [47]. We adapt their task to mode switching with a controller and menu. Bowman et al. introduced TULIP, a menu system using Pinch Gloves^{TM} [5, 6], where each finger represents a menu option which can be selected via pinch. Other examples of 3D menu UI include the ring menu of Gerber et al. [14], a one dimensional list which is wrapped around a ring and controlled through rotation. Many UIs use hand gesture control, such as Laviola et al. [25] and Piekarski et al. [37].

3 DESIGN OF INTERACTION TECHNIQUES

VR provides new ways to design interaction techniques. For a systematic exploration, we grounded our techniques in two fundamental input-theoretic concepts. Figure 2 provides an overview.

3.1 Menu Selection Using Direct/Indirect Input

Input devices can be grouped to direct and indirect input [17]. Traditional devices, such as a mouse, are indirect, as they provide intermediate control of a cursor on a screen that is separate from the user's physical input. Modern devices, such as touchscreens as well a styli, are direct as users directly interact with the target. In 3D, Poupyrev's taxonomy categorises virtual environment manipulation techniques into exocentric and egocentric metaphors [40], we focus on the latter. The virtual hand and virtual pointer represent the majority of egocentric techniques. The virtual hand is essentially direct input — direct grabbing of an object with the hand. The virtual pointer uses ray-pointing, to interact over distance. Both methods are currently used; only the hand is substituted with a controller. Thus we derive our baselines:

Dunk Brush (Figure 2a) Items are selected by directly touching them. Adopting from real-world tasks, this technique may provide advantages over other techniques, since it has a low learning effort. However, a disadvantage is that a physical movement to each object is required rendering this technique only reasonable for physically reachable menus.

Pointer (Figure 2b) Selections are made by pointing at an item and triggering a button. One benefit is that items can be selected from a distance. However, manual effort and jitter are a disadvantage. The user's hand needs to be still while pointing, because little movements can change the pointing direction. Yet, as users interact without occluding the target with their hand and with visual feedback through the cursor, a high precision can be achieved.

3.2 Menu Selection By Gaze Integration

Gaze research in human-computer interaction has shown the potential of utilising visual attention in UIs [4, 7, 21, 49]. In our scenario, natural gaze shifts happen between drawing and menus. While gaze is prone to the Midas Touch problem [21], in this scenario users naturally move their eyes to the menu and, therefore, provide opportunities for enhancements. We contribute three techniques which leverage gaze for menu selection in VR. As previously stated, a limitation of the *dunk brush* direct input technique is interaction over a distance, since physical effort is required when users move to the menu. Hence, we leverage gaze to select the menu mode visually, so users entirely avoid the necessity of physical movement.

Dwell time (Figure 2c) The user's gaze and a specific dwell time is used to confirm selection [21]. The technique was shown to be faster than manual input [43]. A potential benefit is that no physical movement is needed, rendering this technique well-suited for hands-free tasks. However, it adheres to the Midas Touch ambiguity issue and may need more eye coordination from the user. We chose a dwell time of 1 s – long enough to prevent false selections [28].

Next, we designed a technique closer to MAGIC [51] or more recently Pinpointing [24]. The technique departs from the idea of dwell time, i.e. explicit gaze selection, towards an implicit mechanism aimed to eliminate large parts of manual effort through gaze.

Gaze Button (Figure 2d) Gaze is used to point at menu items and a button press is then used to confirm the selection. Similar interaction concepts have shown promising results in other virtual contexts [24, 36]. The user can refine the selection through controller movement while holding the button, where the refinement starts with button down and ends with up. This in principle brings less physical effort, as only small adjustments are needed, but could lead to errors when moving the optional cursor by mistake.

With gaze button, we move from purely eye-based input to a combined gaze and manual input technique. Another approach is to use gaze only to find out which UI is in focus. Gaze-shifting [33] pursues the idea of redirecting manual input between direct and indirect modes. Applied to our context, direct input is active when designing and indirect control of a cursor when the system detects visual attention to the menu. In particular:

Cursor (Figure 2e) when users look at the menu, they can move a cursor using controller movement. The technique uses a 1:1 mapping between controller and cursor. Here gaze is only used to indicate the user's context switch to the menu. When on the menu, the user controls a cursor. It is controlled like a touchpad and can be moved through controller movement when the button is pressed. An advantage may be precision from fine-grained cursor movements. A potential disadvantage is time loss from cursor movement.

In sum, the first two techniques, *Dunk Brush* and *Pointer*, are the status quo of current menu UI. Leveraging gaze data, three further techniques become possible for task-menu switching: *dwell time*, *Gaze button*, and *Cursor*. The techniques are evaluated as follows.

4 USER STUDY

The goal of the study is to explore the research question of *how do variations of multimodal gaze and manual interaction techniques affect the user's performance in the interaction with menus?*

4.1 Study Design

We designed a within-subjects user study to evaluate the five different menu selection techniques (independent variables) in a 3D drawing scenario in VR. Our study explores the effect of each technique on the task completion time, physical effort, eye fatigue, and subjective ratings (dependent variables). The order of different selection techniques was counter-balanced using a Latin square. As only 15 users fit a perfect Latin square, the remaining two users were randomly assigned to order groups. The second independent variable, order of the menu sizes (4 or 16 colours) was randomised.

4.2 Apparatus

We used the HTC Vive HMD (1080 × 1200 px per eye, 90 Hz, 110° FOV), with the Tobii Pro VR Integration eye tracker(120 Hz, 0.5° accuracy). The software is coded in Unity with SteamVR/TobiiXR.

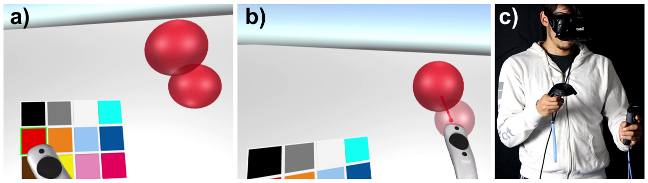


Figure 3: Examples showing (a) menu selection with Dunk Brush, (b) connecting the spheres, (c) outside user view.

4.3 Task

We designed a drawing task inspired by Surale et al. [47], in which the user has connects two spheres by drawing a 3D line between them in the colour of the two spheres. Each new pair of spheres appears when the previous pair is connected correctly.

The radius of each sphere is 50 mm. The distance between the spheres from centre to centre is 150 mm. The position of each sphere is randomly chosen within a cubical work area (300 mm × 300 mm × 300 mm). The position of the work area is 200 mm in front of the participant's head, so every sphere can easily be reached, (cf. Figure 3). All tasks were performed in a sitting position.

A sphere (diameter 2 mm) is attached to the controller in the user's dominant hand, representing the brush. The brush sphere is the anchor of the drawn line and always displays the selected colour. To draw a line, participants have to move the dominant hand with the controller until the brush sphere inside one of the target spheres (indicated by a change of opacity). Then they can start drawing by pressing the trigger button. When the second sphere is reached, the trigger button can be released to finish line drawing. Wrong lines (false colour or not connecting spheres) stay visible until redrawing a line.

A colour menu in the form of a flat cuboid, sized 200 mm × 4 mm × 200 mm, is attached to the controller of the non-dominant hand, similar to a traditional colour palette (cf., Figure 3). While the size of the menu itself does not change, we vary between a menu with four colour options and one with 16 options. For the *Gaze button* and *Cursor* techniques, a cursor in the shape of a sphere with a diameter of 20 mm is added to the menu. It changes colour depending on which colour it touches or is closest to.

4.4 Participants

We invited 17 participants to take part in our study (7 female, 14 right-handed). Participants were on average 24 years old (*mean = 24.24, std= 2.56*). Five participants wore glasses and one wore contact lenses. They also rated their experience with VR and gaze interaction on a Likert scale (1=no experience, 5=very experienced). They rated themselves as moderately experienced with VR (M=2.7, SD=1.56) and less experienced with gaze interaction (M=2, SD=1.24).

4.5 Procedure

First, the procedure and goals of the study were explained. We asked all participants to fill in consent forms and answer demographics questions. Participants were then asked to put on the HMD in a seated position and the task was explained. The eye-tracker was calibrated once at the beginning of the session. Our tests during the

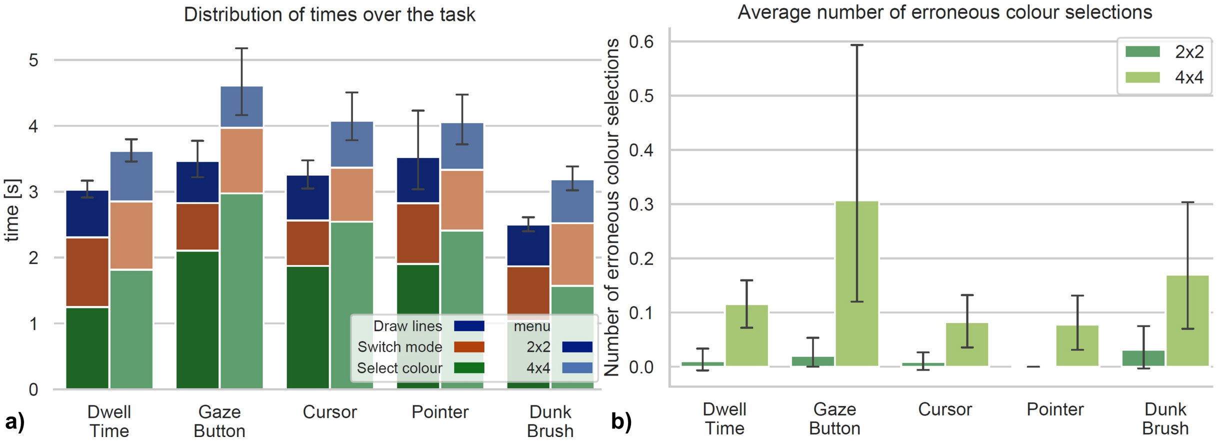


Figure 4: (a) Results on task completion time indicating superior performance of Dunk Brush and Dwell Time. *Dark/light bars correspond to 2x2/4x4 menus.* (b) Erroneous colour selections, showing that error increases with menu size.

development showed the used hardware did not experience inaccuracy issues for its advanced slippage compensation to maintain the accuracy and calibration, it was not necessary to assess calibration accuracy and recalibrate users (e.g., in contrast to [31]).

At the beginning of each new technique, participants practised selecting a colour for one to five times. Then, the blocks started for each condition. After each block, users had the option to take a break. Then, we introduced the next technique. Users conducted 2 blocks, one for each menu size. This was repeated for each technique, producing 20 lines × 2 colour menu sizes × 5 techniques = 200 lines per participant. After each technique, participants rated their agreement to six Likert scale statements, assessing the ease of use, learnability, eye comfort, physical effort, speed and precision of the different techniques (1=strongly disagree; 5=strongly agree).

5 RESULTS

We report on the participants' performance with the techniques. We investigate quantitative aspects and present user feedback. Shapiro-Wilk tests showed that task completion times, error, and physical movement data was not normally distributed. Hence, we used a Friedman test with post-hoc Wilcoxon signed rank tests (Bonferroni corrected). The error bars in diagrams are 95% confidence intervals.

5.1 Task Completion Time

We tracked the following times: (1) the overall time for successfully connecting the spheres (*overall*); (2) the time until the correct colour was selected (*switch-1*); (3) the time between colour selection and start of drawing (*switch-2*); and (4) the time taken to draw a line (*draw*). A visual overview can be seen in Figure 4a. A Friedman test showed that our *techniques* had significant effects on all times ($p<.001$, Overall: χ^2=31.39, Colour: χ^2=47.44, Switch: χ^2=37.32) but the time to connect the spheres (p=.138). This is expected, as the line drawing task was identical for all conditions. In the following we report on the post-hoc tests for the significant sub-tasks.

Time overall (Figure 4a, full bar). We find Dunk Brush to be significantly faster than Gaze Button (Z=-3.43, w=4, p=.006) , Cursor (Z=-3.38, w=5, p=.007) and Pointer (Z=-3.43, w=4, p=.006). Menu size had a significant effect as well with smaller menus leading to shorter times (Z=-3.57, w=1, p<.001).

Time needed to select the correct colour. Post-hoc comparison between conditions showed Dunk Brush to be significant faster than all other techniques (Dwell Time: p=.042 (w=16, Z=-2.86), Gaze Button: p=.003 (w=16, Z=-2.86), Cursor: p=.003 (w=0, Z=-3.62), Pointer: p=.005 (w=3, Z=-3.48)). Furthermore we found Dwell Time to be significantly faster than Cursor (Z=-3.2427, w=8, p=.012) and Gaze Button (Z=-3.62, w=0, p=.003). Smaller menus led to significantly shorter times (Z=-3.57, w=1, p<.001).

Time from selecting the correct colour until starting to draw the line. The post-hoc tests show users were significantly faster with the Cursor technique compared to both Dwell Time (Z=-3.43, w=4, p=.006) and the Pointer (Z=-2.91, w=15, p=.036) technique. Menu size had a significant effect on this time as well with smaller menus leading to faster switches (Z=-1.59, w=43, p<.001).

In sum, we find Dunk Brush performs best overall and for colour selection. Interestingly, the two switch times revealed inverse results for Dwell Time and Cursor: Dwell Time is faster to select a colour, but Cursor faster to return to drawing after colour selection.

5.2 Erroneous Colour Selections

The number of erroneous colour selections denotes how many times users selected the wrong colour before selecting the correct one to finish the task. Figure 4b shows the results for each condition. The larger value and error bar for Gaze Button with a 4×4 menu may be attributed to a single participant. One potential reason is eye-tracking inaccuracy for this user, which could also lead to more use of the refining feature of Gaze Button that adds time. The number of menu options has a statistically significant effect on error (Z=-36219, w=0, p<.01), showing that more menu items lead to more errors. Technique on the amount of colour selections did not reveal significant differences (χ^2=6.44, p=.17).

5.3 Physical Movement

In addition to task completion times, we compare *physical movement* across the techniques, which can be indicative of physical effort exhibited during the task. This includes motion of both hands,

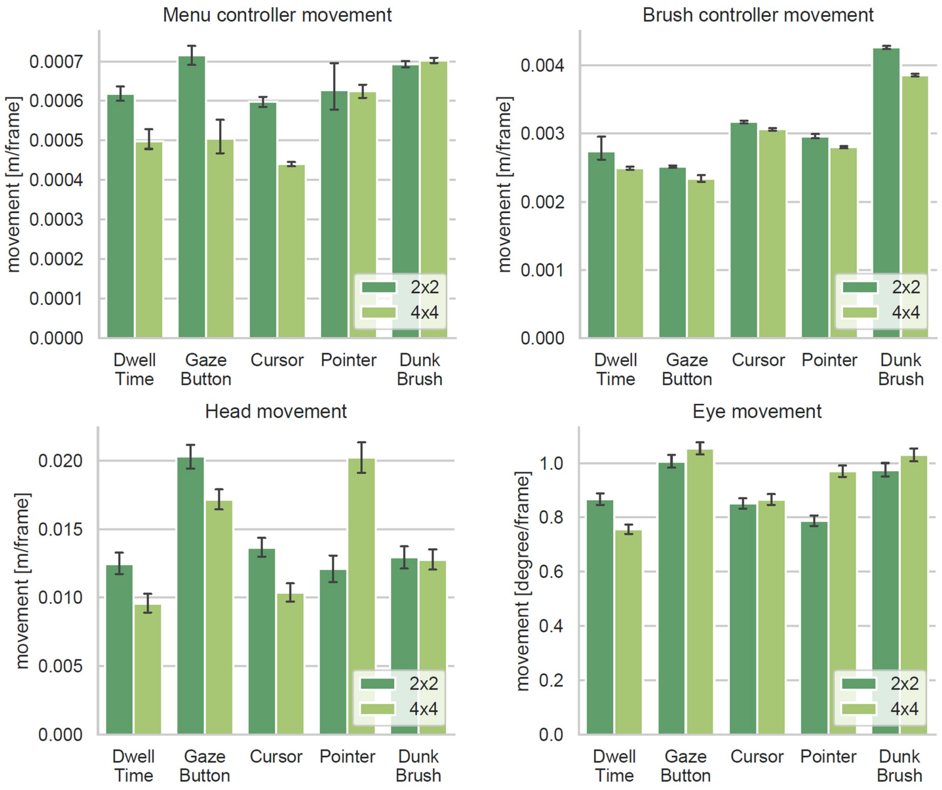


Figure 5: Average physical movement effort for techniques and menu sizes of hands, head and eyes.

head, and eyes. All motions, except eyes, are calculated as average movement per frame. Eye movement is calculated as average angular rotation per frame. Results are shown in Figures 5 and 6.

We found no significant effects of the technique on eye movement (p=.117) or head movement (p=.629). There was a significant effect on menu controller movement (χ^2=10.92, p<.028), but no post-hoc comparisons have been found with significant differences. In addition, menu size had an effect on movement of the brush controller (Z=-3.574, w=1, p<.001) with a larger menu leading to more movement. We found a significant effect on the movement of the brush controller that is held in the dominant hand (χ^2=47.86, p<.001), leading to following findings:

Dunk Brush exhibits highest physical movement. Post-hoc analysis revealed that Dunk Brush included significantly more movement of the brush hand than all other conditions (Z=-3.62, w=0, p<.001), which is expected as the technique involves movement by design.

Pointer and Cursor lead to higher movement than Dwell Time. Post-hoc tests show that Pointer and Cursor induced significantly more movement than Dwell Time (Pointer: Z=-2.86, w=16, p=.042; Cursor:Z=-3.0, w=13, p<.026). It was expected that Dwell Time has lower movement, as an eye-only based technique.

Pointer and Cursor induce higher movement than Gaze Button. Pointer and Cursor exhibited more movement than Gaze Button (Pointer: Z=-2.91, w=15, p=.036; Cursor:Z=-3.48, w=3, p<.001). This is somewhat surprising as Gaze Button integrates both gaze and manual input. As a potential reason, the need to initially position a cursor (the ray cursor with Pointer, and the menu cursor with Cursor) is likely to have caused the additional movement. With Gaze Button, manual input occurs after users have positioned a cursor by gaze, to refine its position with hand movement. However, this movement has not been found as significantly pronounced. This indicates that, instead of refining the position, users rather restarted the colour selection at the expense of more errors (Fig 4b).

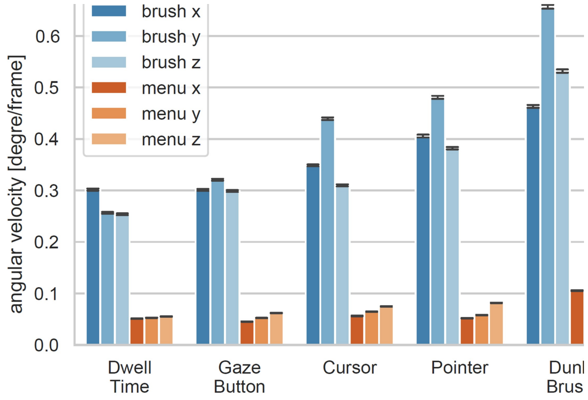


Figure 6: Rotational effort for all techniques and hands estimated by the average angular velocity for all rotation axes.

5.4 Physical Rotation

Some participants reported not liking Pointer due to the *wrist rotation* when pointing at the non-dominant hand. To investigate this

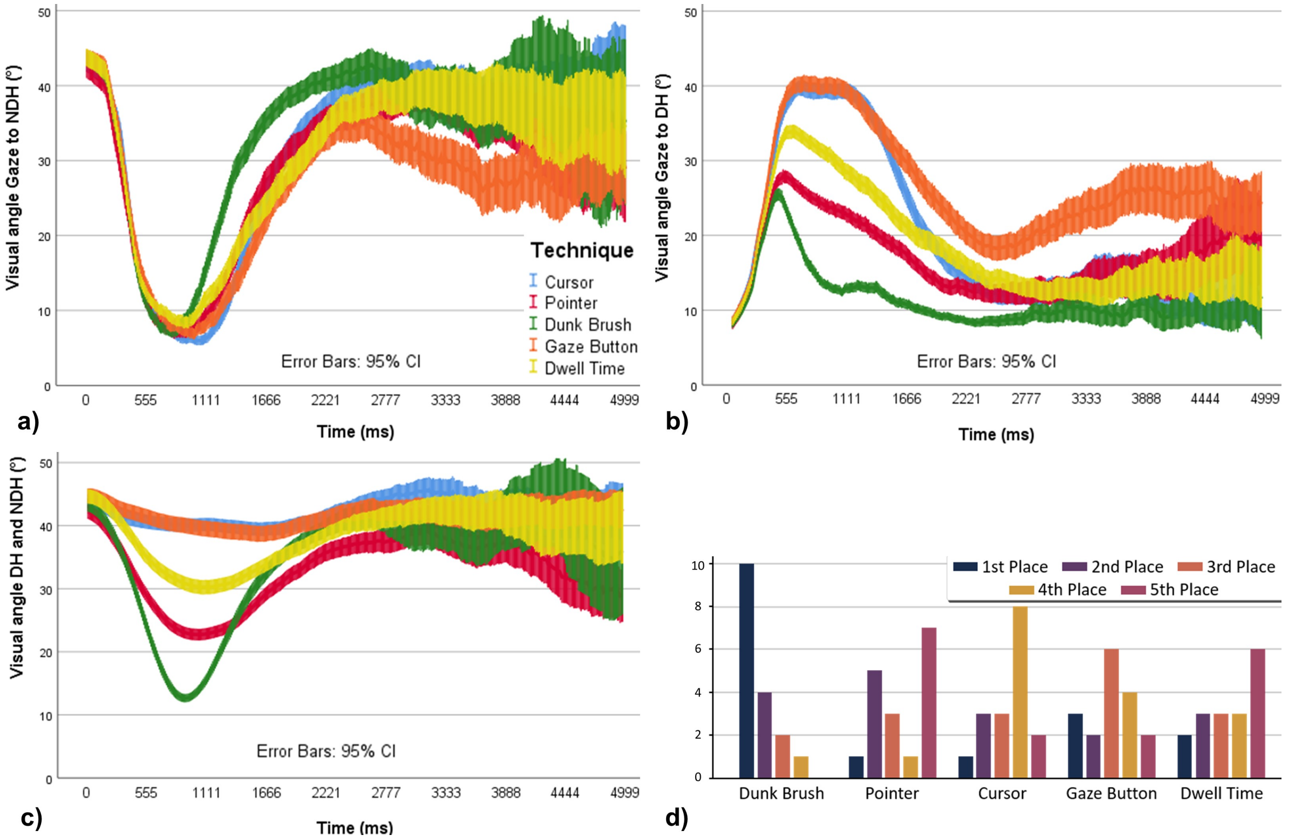


Figure 7: Eye-hand coordination (a-c): How the users coordinate hands and eyes (in visual angle, i.e., user's perspective). a) shows how the user's gaze is directed toward the menu (held in NDH) at about 1000ms to select the colour - consistent across all techniques. b) shows a strong eye-dominant-hand coupling for Dunk Brush, while the raw eye-based techniques (e.g., Dwell Time), are most decoupled. c) shows how closely users utilise both hands, and surprisingly users with Pointer move toward the menu even if redundant. d) Distribution of participants final rankings of the techniques.

further, we calculated average angular velocity across all axes for both hands and all techniques (cf. Figure 6). We found menu size to significantly impact rotational demand for all axis of the brush controller(x: p=.003, y: p=.017, z: p=.025). We found no effect on rotation for the menu controller. We found significant effects of the techniques on all average velocities across x, y and z-axes, both for the menu controller (33.45<χ^2<=44.00, p<.001) and the brush controller (33.69<χ^2<54.36, p<.001).

Dunk Brush had the highest average velocity. Post-hocs revealed that the angular velocity of Dunk Brush was significantly higher than all other techniques for both controllers with the only exception of the x-axis of the brush controller and the Pointer technique.

Pointer caused the second highest angular velocities. Pointer led to significantly increased rotation than dwell time for all axis of the brush controller movement (Z< -2.91, 0<=w<=15, p<.042). In addition it caused increased rotation in the brush controller (y-axis) compared to Gaze Button (Z=-3.20, w=9, p=.014) and in the menu controller (z-axis) compared to Dwell Time (Z=-3.15, w=10, p=.016) and Gaze Button (Z=-2.82, w=17, p=.049).

5.5 Coordination

Where and how the user is directing their eyes and hands is inherently affected by the design of the interaction techniques. Here we explore in-depth how these parts have been coordinated during the interaction. The coordination is interesting for both task parts: for using the menu and selecting a colour, as well as when users draw the line. To analyse this, we consider *degree of visual angle*, i.e., how far the objects are away from each other from the user's perspective, *over time of each trial.* For each frame, we first compute three rays and then compute their angular distance. The rays are: (1) Gaze, the ray from the head position to where the user is looking at, (2) DH, the ray from head position to dominant-hand-held controller position (pen), and (3) NDH, the ray from head position to nondominant-hand-held menu's target colour position. Figure 7 shows the coordination between the objects. The smaller the angles, the closer are the rays. The lines thickness denotes the 95% confidence intervals for each frame. From visually analysing the trends, we find the following insights of interest:

Gaze and task coordination pattern is similar across techniques. The visual attention shifting nature of the menu interaction is apparent across the techniques. Figure 7a shows a shift of the user's visual attention close to the NDH (menu) that user initially focus on to find the right colour. Then, Figure 7b shows that gaze shifts to the DH holding the brush where it becomes important to see what is drawn. This shows that using the mode switch leads to a gaze behaviour of shifting from one to another hand's visual area, confirming and quantifying what we sketched in Figure 1.

Gaze decouples the hands more than indirect input. Figure 7c shows how close users' hands are in visual space. With Dunk Brush as a direct technique, hands are held closest. All other techniques utilise indirect input, yet vary substantially between visual angle of hands. Surprisingly, Pointer led to users moving the DH closer to the NDH than others, even if not required. This might result from users being familiar with ray casting and instinctively moving towards the menu. In contrast, Dwell Time and Gaze Button reveal low coordination needs, being completely based on gaze pointing.

Dunk Brush is fastest, but requires most movement. When observing the angle between gaze direction and head to controller direction (Figure 7b), it can be seen that participants almost always look at the controller. They only stop to do so when shortly looking to the menu UI around 500 ms, when finding the target colour from the menu. Around 1000 ms the angle increases slightly again. A reason might be, that participants already looked at the spheres as they already move the controller in that direction (Figure 7d). Afterwards, gaze follows the controller to draw the line.

5.6 Subjective Ratings

The provided feedback was tested for significance by applying non-parametric Durbin tests (factors: menu size and technique) and Conover's post-hoc tests. Ratings are shown in Figure 8. We report on all self-reported usability aspects: ease, learnability, eye tiredness, physical effort, precision, and speed.

Dunk Brush perceived as easier to use, faster, and easier to learn. Dunk Brush was reported as significantly *easier to use* (Median=5) than all other techniques (Medians=3.5–4, p<.001). It was also perceived significantly faster (Median=4.5) than all other techniques (Medians 4, p<=.015). For perceived *learnability* (p<.001), Conover's post-hoc revealed that Dunk Brush was perceived as significantly easier to learn (Median=5) than Gaze Button, Cursor and Pointer (Median=4, p<=.005), but not for Dwell Time.

Pointer and Dwell Time perceived as easier to learn than Gaze Button. Pointer and Dwell Time (Medians=5) were also perceived as significantly easier to learn than Gaze Button (Median=4, p<=.013).

Gaze Button and Dwell Time perceived as more eye-tiring. When asked about the caused *eye tiredness*, participants found both Gaze Button and Dwell Time significantly more eye tiring, (Median=4) than all other techniques (Median=5, p<=.005).

Dwell Time perceived as less physically demanding than Cursor and Pointer. Users rated Dwell Time to exhibit significantly less *physical effort* (Median=4) than Cursor (Median=3, p=.029) and Pointer (Median=4, p=.031).

Dunk Brush perceived more precise than Dwell Time and Gaze Button. We found significant effects on the reported *precision* (p<.001). Dunk Brush was perceived as more precise (Median=5) than Dwell Time and Gaze Button (Medians=4, p<=.03).

Gaze Button perceived as least precise. Gaze Button was rated less precise than all other techniques (Median=4, .006<=p<=.048). This is surprising, as the Dwell Time approach has the same selection mechanism by gaze, but Gaze Button has the additional feature of refining the gaze-selected position. One explanation is the need to synchronise both modalities, adding temporal precision effort.

5.7 Ranking and Feedback

After finishing all tasks of the user study, we asked participants to fill in a final questionnaire on their overall perception. Participants were asked to first rank all techniques based on their personal preferences. Figure 7d shows the distribution of these rankings. Dunk Brush was ranked highest, followed by Gaze Button; Cursor; and Pointer and Dwell Time were both ranked lowest.

We asked the participants to give reasons for their rankings. Participants mentioned the natural, intuitive and easy usage of Dunk Brush as their main reason for preferring this technique (10 mentions). The gaze based techniques were especially liked for causing little physical effort (5 mentions). The one participant that preferred Pointer over all other techniques based his decision on previous experiences with this technique. When asked for their reasons for ranking Pointer last, participants mentioned the difficult, awkward and not intuitive/natural usage (6). Dwell Time was not liked for being slow (3) and eye tiring (2).

6 DISCUSSION

We investigated the continuum of potential interaction techniques between fully gaze to manual interaction, on the scenario of interacting with menu UIs. Our comparative study revealed insights into the trade-offs between gaze to manual, direct and indirect input methods. We discuss main findings, design recommendations, and threads to validity.

6.1 Main Findings

6.1.1 *Performance.*

Using Dunk Brush allows users to be most efficient and fast for the tested colour switching task. For tasks that are usually conducted with a Pointer, user performance is comparable with the gaze variants of Dwell Time, Gaze Button, and Cursor. Among the gaze techniques, Dwell Time was the fastest as an eyes-only technique.

6.1.2 *Physical Effort.*

The manual techniques led to significantly more physical movement across the tested factors than the gaze techniques. This indicates that leveraging gaze can make interactions less physically demanding; an important aspect when interaction involves frequent switching. Within the gaze techniques, Cursor involved more movement than Dwell Time and Gaze Button.

6.1.3 *Coordination.*

By design, users move their dominant hand closest to the menu with the Dunk Brush technique. Users keep their eyes always close to the hand and only briefly look to the menu for predictive targeting. We also found that for Pointer and Cursor, where users do not need to move their hands, users were inclined to move towards the target nonetheless. This suggests that some manual activity happens unconsciously, even if the technique

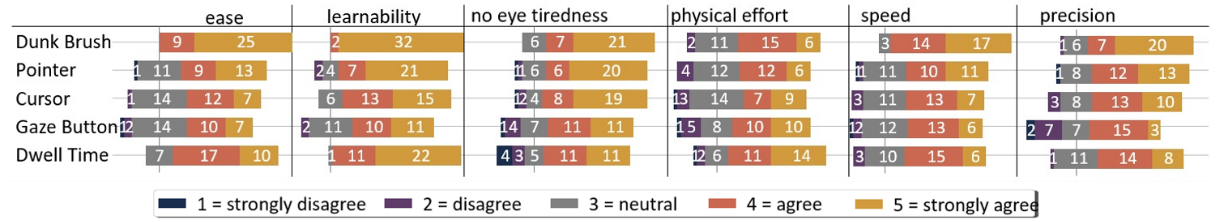


Figure 8: Likert-scale feedback on the usability questionnaire, indicating qualitative differences between the techniques.

is designed not to require it. However, for techniques were the pointing subtask is allocated to gaze only (Dwell, Gaze Button), no additional manual activity is conducted.

6.1.4 *User Perception.*

Overall perception correlates with performance. Dunk Brush was rated more precise, easier to use and easier to learn. Pointer and Dwell Time were perceived as easier than Gaze Button. Thus, a combination of the controller button with gaze may need more learning effort in the context we investigated.

6.1.5 *Eye/Physical Fatigue.*

We find that the more eye-input is used, the more does the eye-fatigue increase but simultaneously the manual effort decreases. Users perceived Gaze Button and Dwell Time as more eye tiring; not so the Cursor method. Users found Dwell Time to require less physical effort than both Pointer and Cursor. Pointer and Cursor both require users to conduct a form of pointing with effort. The Cursor technique used a 1:1 mapping between controller and cursor. This could potentially improve with dynamic control display gains, as implemented with the mouse.

6.1.6 *Preferences.*

User preferences correlate with their performance, with Dunk Brush preferred. Gaze Button was second most popular – despite performance issues, users were positive about it. Contrasting performance, Dwell Time was ranked lowest, which can be accounted to the higher eye fatigue. Pointer also ranked lowest, relating to our observation that users needed a lot of controller movement and rotation to accomplish tasks.

6.2 Design Considerations

We present design considerations based on benefits and limitations.

6.2.1 *Dunk Brush fit for menus in reach.*

In our scenario, the Dunk Brush method is favoured, as it is easy and supports natural movement like in the real world. This makes it fit for our menu UI that mimicked a painter's palette; but is limited for out-of-reach UIs.

6.2.2 *Gaze techniques can improve Pointer.*

Pointer is used for many applications, but was not well received in our scenario as shifting between menu and main canvas required rotating the controller. With users stating it to be less suitable and more physically demanding for handheld menus, the gaze techniques have potential to make menu interactions easier.

6.2.3 *Cursor trades physical effort with precision.*

The Cursor technique has been stated to require a lot of movement. Hence, when working with large menu UIs, a more dynamic cursor movement mapping might be useful. This is standard in desktop input devices, such as the mouse or touchpad. The application of this technique could be subject to further studies, as in principle the use of the cursor allows to select very fine grained targets.

6.2.4 *Dwell time is fast but feels slow.*

For dwell time, users performed second fastest, but disliked to wait and stated to prefer shorter selection times. For colour selection, a shorter dwell time might be possible. However, the risk of a undesired 'Midas touch' increases, which might annoy the user. Another challenge might be that after selecting a colour in the middle of the colour palette, users might look away from the menu, but while doing so, select another colour on the palette by mistake.

6.3 Threads to Validity

This work has several limitations. The user's performance with the Gaze Button technique is only partially understood. The result of lower performance indicates potential issue with to the refinement feature that costs time, or the synchronisation effort between the two modalities. Other papers found similar results [35], and it demands further studies to grasp this issue. Our study involved participants from the local university who are of student background, which is one of the target groups of the VR systems, however it would be interesting to expand to others too. In addition, while we believe that our work can generalise to other gaze + manual UIs, our focus was on techniques that utilise a VR controller and it would be interesting to see if they apply to other input methods such as free hand gestures [47] as well.

7 CONCLUSION

We investigated how we can utilise visual attention switches in tasks of drawing and menu interaction. We designed three interaction techniques – each with a different ratio between use of eye and manual input. We presented a user study that compares the techniques to two status-quo baselines of indirect pointing and direct reaching. Our analysis provides a detailed characterisation of strength and weaknesses of the techniques for the tested task. Our work is useful to inform the design of gaze interaction techniques that are integrated into complex task environments, such as bimanual compound tasks of mode switching and menu UIs.

In the future, more interaction capabilities can be investigated, for example, using the trigger button of the non-dominant hand. This removes the need for a button on the controller in the user's dominant hand and enables using a simple pen device. Evaluating the techniques Gaze Button and Cursor for a distant menu UI could be interesting in the future. The optional cursor of Gaze Button could be used for an underlying menu in a menu hierarchy, meaning that gaze selects which sub menu will be opened, whereas the cursor selects the item of the sub menu.

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