

Investigating Visual Feedforward for Expanded Selection Areas in Gaze-Based Interfaces

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Expanding an object's region in motor space (selection area) using Voronoi tessellation can facilitate the selection of small targets in gaze-based interfaces. While visual feedforward, such as visualizing the selection area, has been shown to improve selection performance in hand-based interfaces, its influence on gaze-based interfaces remains unclear. To address this, we conducted two user studies to examine how visual feedforward affects fixation behavior and selection performance when the centers of a target and its selection area differ. The results reveal that visualizing either the selection area or its center effectively guides users' gaze toward the center of the selection area, thereby improving selection accuracy. Furthermore, displaying a gaze cursor reduces errors by enabling users to adjust their fixation, even though it does not directly guide gaze toward the center of the selection area.

CCS Concepts: • **Human-centered computing** → *Mixed / augmented reality*; **Pointing**.

Additional Key Words and Phrases: Mixed Reality, Gaze-based Interface, Visual Feedforward

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1 Introduction

As eye trackers are being increasingly integrated into commercial head-mounted displays (HMDs), gaze-based interfaces are becoming more prevalent in virtual reality (VR) and mixed reality (MR) environments [Cournia et al. 2003; Tanriverdi and Jacob 2000]. In gaze-only interfaces, users select targets by fixating somewhere within a target's selection area for a specified duration (dwell-time selection). We use the term *selection area* to denote the motor-space activation region—that is, the region in which a gaze dwell triggers selection. The selection area may differ from the target's visual region; in other words, its size in motor space can differ from that in visual space.

To facilitate the selection of small objects in gaze-based interfaces, researchers have proposed methods that preemptively expand object size only in motor space using spatial partitioning techniques [Choi et al. 2020; Sidenmark et al. 2024], such as Voronoi tessellation [Fortune 1987]. These methods enlarge an object's selection area by dividing and assigning the surrounding space to the nearest objects. Such approaches are well suited to real-world object selection scenarios because physical objects cannot be arbitrarily repositioned by the system, unlike virtual objects [Deng et al. 2017; Wang and Kopper 2021], which can be moved. Since selecting real-world objects requires the dynamic assignment of selection areas [Fashimpaur et al. 2025; Lee et al. 2024; Toyama et al. 2012], Voronoi-based expansion provides a practical means to assign and enlarge selection areas simultaneously.

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In this study, we investigated suitable forms of visual feedforward in gaze-based interfaces with selection area expansion using Voronoi tessellation. Previous studies have primarily examined the selection performance of visualizing the selection area [Wang et al. 2024; Zhang 2024] but have not compared performance across different types of visual feedforward. To address this gap, we compared the selection performance of the following visual feedforward types: visualizing the selection area, visualizing the center of the selection area, and displaying a gaze cursor.

We specifically focused on cases in which the center of gravity (CoG) of a target in visual space differs from that in motor space. Such misalignment frequently occurs in densely packed environments [Baudisch et al. 2008]. In such a situation, users are likely to fixate on the target's CoG when the selection area is invisible, because humans tend to fixate on the visual-space CoG of objects [Melcher and Kowler 1999]. However, in densely arranged layouts, gaze data often extends into adjacent selection areas, thus reducing selection accuracy even when the selection area is sufficiently enlarged. We hypothesized that appropriate visual feedforward could shift users' fixation toward the selection-area CoG by altering the target's visual-space CoG, thereby improving selection accuracy.

Based on this hypothesis, we address the following research questions in this study: **[RQ1]** Can visual feedforward that alters a target's visual-space CoG guide fixation from the target's CoG toward the center of its selection area? **[RQ2]** Which form of visual feedforward most effectively improves selection accuracy in gaze-based interfaces?

To address these questions, we conducted a user study to examine selection performance and fixation behavior under different visual feedforward conditions. The results showed that visualizing either the selection area or its center effectively guided users' fixations from the target's CoG toward the selection area's CoG, thereby improving selection accuracy. By contrast, a gaze cursor improved selection accuracy without inducing such a fixation shift. In a follow-up study, adding the gaze cursor across all conditions led to further improvements in selection accuracy by enabling users to adjust their fixation positions.

This study makes three contributions: (1) Evaluating the effect of visual feedforward on selection accuracy when the target's center and the selection area's center are misaligned. (2) Demonstrating that visualizing either the selection area or its center effectively guides users' fixation toward the selection area's center, thereby improving selection accuracy. (3) Showing that combining these visual feedforward with a displayed gaze cursor further enhances selection accuracy.

2 Related Work

2.1 Expanding the Selection Area

To facilitate the selection of small objects, several methods have been proposed that pre-expand target size only in motor space [Choi et al. 2020; Miniotas et al. 2004; Niu et al. 2024]. The simplest approach enlarges targets in both visual and motor spaces by displaying a zoomed-in window [Lankford 2000; Sato et al. 2025; Skovsgaard et al. 2010]. However, this increases selection time due to the additional operation required to invoke the zoomed-in window. By contrast, pre-expanding target size in advance reduces the time needed for enlargement, while expanding only in motor space avoids the occlusion of peripheral information that occurs with visual zooming [Choi et al. 2020; Miniotas et al. 2004]. This approach prevents overlap between selection areas and effectively facilitates the selection of small targets across mouse- [Findlater et al. 2010; Grossman and Balakrishnan 2005; Mott and Wobbrock 2014], controller- [Baloup et al. 2019; Vanacken et al. 2007], and gaze-based interfaces [Choi et al. 2020; Sidenmark et al. 2024].

When expanding a selection area using Voronoi tessellation, the CoG of the selection area does not coincide with the CoG of the object unless the objects are perfectly aligned [Du et al. 1999].

Moreover, as object density increases, the degree of misalignment may also become larger. Such situations are common in practical applications, including selecting markers on a map [Baudisch et al. 2008], selecting items from a store display [Lee et al. 2024; Mayer et al. 2020], or selecting clothes from a tightly arranged shelf [Lee et al. 2024]. Previous research has primarily focused on the problem of insufficiently expanded selection areas in high-density situations [Choi et al. 2020; Findlater et al. 2010; Mott and Wobbrock 2014], while the impact of this misalignment on selection performance has not yet been investigated.

2.2 Visual Feedforward for Expanded Selection Areas

In hand-based interfaces, visual feedforward has been shown to influence selection performance for targets with expanded selection areas [Baloup et al. 2019; Guillon et al. 2014, 2015; Su et al. 2014]. Previous studies reported that visualizing the selection area and highlighting hovered objects were effective [Baloup et al. 2019; Guillon et al. 2014, 2015; Su et al. 2014]. By contrast, the *bubble cursor* [Grossman and Balakrishnan 2005], which dynamically adjusts the cursor size to encompass the object, was found to degrade performance [Baloup et al. 2019; Guillon et al. 2015].

In gaze-based interfaces, the impact of visual feedforward on object selection performance has been scarcely investigated [Wang et al. 2024; Zhang 2024]. These studies only examined selection performance for different combinations of target sizes in visual and motor spaces. Zhang et al. [Zhang 2024] reported that selection time using the dwell-time selection method was significantly faster for invisible selection areas than for visible ones. By contrast, no comparative studies have investigated the performance of gaze-based interfaces across various types of visual feedforward.

Unlike mouse interfaces, gaze-based interfaces often omit the cursor, as displaying gaze position is not essential for interaction [Jacob 1995]. Thus, a gaze cursor can be regarded as a form of visual feedforward. In dwell-time selection, two studies found no significant effect of a gaze cursor on performance [Alonso et al. 2013; Zhang et al. 2011], whereas another reported that it significantly reduced selection time [Wei et al. 2025]. The latter suggested that the gaze cursor serves as a cue for users' current fixation, thereby improving performance. However, the effect of a gaze cursor on selection performance in the context of expanded selection areas remains unexplored.

2.3 Human Fixation Behaviors

Saccades toward an object typically land near its CoG [Melcher and Kowler 1999], and fixations reveal a similar pattern [Melcher and Kowler 1999; Richards and Kaufman 1969]. Initial fixations are generally directed to the CoG for both 2D [Melcher and Kowler 1999; Richards and Kaufman 1969] and 3D objects [Brouwer et al. 2009; Schuetz and Fiehler 2024; Vishwanath and Kowler 2004]. With subsequent refixations after the initial saccade, fixations often shift toward functional regions (e.g., the spout of a teapot) [Roberts and Humphreys 2010; van der Linden et al. 2015].

In gaze-based menu interfaces, users also tend to fixate on the CoG of a circular or square menu item, which coincides with the optimal fixation position. Fixating on this point helps keep gaze dispersion within the selection area, whereas fixations near the edge increase the likelihood that the gaze will drift beyond the target. To minimize gaze drift toward peripheral areas, Apple recommends using rounded elements and placing text or glyphs centrally.¹

However, when the target's visual CoG and the selection area's CoG differ, the user's fixation position no longer aligns with an optimal fixation position. In such cases, even though the optimal fixation point lies at the center of the selection area, users tend to fixate on the target's CoG instead. Therefore, it is important to establish a feedforward design strategy that guides users' gaze toward the center of the selection area when expanding selection areas.

¹<https://developer.apple.com/videos/play/wwdc2023/10073/> (accessed: September 30, 2025)

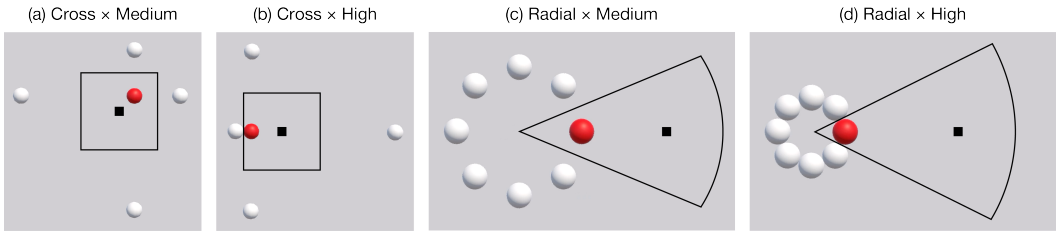


Fig. 1. Object layouts and target selection areas for each combination of *Layout* and *Center Offset*. The red sphere represents the target, and the white spheres represent distractors. The areas enclosed by solid black lines indicate the target's selection area, while the black squares (■) mark the centers of the selection areas.

3 Study 1

To answer RQ1 and RQ2, we conducted a study to examine whether visual feedforward can guide users' gaze toward the center of the selection area, and thus, improve selection performance. The study task was performed in an MR environment. Moreover, the study was approved by the ethics review committee of our institute (number 2024R859).

Eighteen participants (2 female, 16 male; mean age = 22.9 years, $SD = 1.1$, IDs: 1–18) were recruited from a local laboratory. All participants had normal color vision. Among them, nine had normal vision, three wore glasses, and six used contact lenses. Additionally, nine participants had prior experience with gaze-based interfaces. Each participant received US\$12 as compensation for participation, and each session lasted approximately 60 minutes.

3.1 Selection Area Design and Object Layout

3.1.1 Expansion Algorithm for Selection Area. We utilized Voronoi tessellation to expand each object's selection area and then clipped these areas using a circular region with a fixed radius (*cut-off radius* [Choi et al. 2020]). In dwell-time selection methods, it is not advisable to use the entire field of view as the selection area [Choi et al. 2020], since dwell time may accumulate at any point of interest and could trigger unintended activations [Jacob 1990] across the entire space. Therefore, clipping was applied to each selection area to constrain it to an appropriate size.

3.1.2 Definition of the Center of the Selection Area. We defined the *center of the selection area* as the optimal fixation point, which represents the position within the area that best accounts for gaze dispersion. In other words, the center corresponds to the center of the largest inscribed circle within the selection area—that is, the point farthest from its boundary. Moreover, the center of the selection area may differ from its CoG, as in the case of a circular sector.

3.1.3 Layout of Target and Distractors. We designed four layouts, each consisting of one target and multiple distractors, in which the target and the center of its selection area were spatially misaligned. These layouts were defined by the combination of two *Layout* types (*Cross* and *Radial*) and two *Center Offset* levels (*Medium* and *High*) (Fig. 1).

Layout refers to the spatial arrangement of objects. In the *Cross Layout*, the target is surrounded by distractors positioned above, below, left, and right (Figs. 1a and 1b). This configuration has been widely used in studies on target expansion techniques [Chapuis et al. 2009; Choi et al. 2020; Grossman and Balakrishnan 2005; Su et al. 2014]; the resulting selection area forms a square. By contrast, the *Radial Layout* arranges distractors uniformly around the target at the eight cardinal and intercardinal directions; this forms a circular configuration [Shi et al. 2023; Waugh et al. 2025] (Figs. 1c and 1d). In this case, the target's selection area takes the shape of a circular sector.

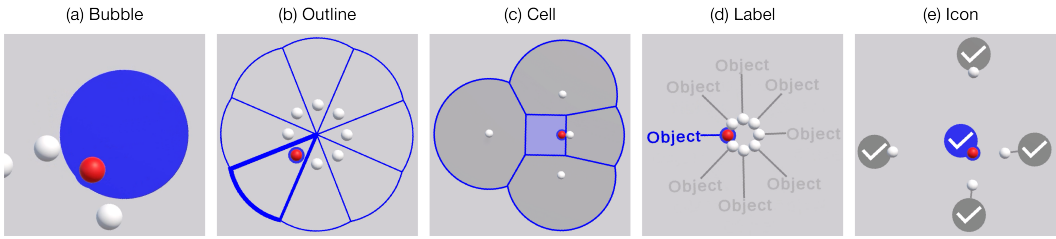


Fig. 2. Five types of visual feedforward designed for this study. In all panels, the user fixates within the target's selection area.

The *Cross* and *Radial* layouts were chosen for two main reasons: (1) their general geometric configurations have been examined in prior research [Chapuis et al. 2009; Choi et al. 2020; Grossman and Balakrishnan 2005; Shi et al. 2023; Su et al. 2014; Waugh et al. 2025], and (2) they allow systematic adjustment of the center offset. In addition, these layouts differ in the characteristics of their selection areas: the *Cross* layout yields a finite target Voronoi region, whereas the *Radial* layout yields an unbounded region that is clipped by the cut-off radius.

Center Offset refers to the spatial offset between the center of the target and the center of its selection area. The *High Center Offset* indicates the maximum offset, in which the target is positioned in direct contact with an edge of its selection area (Figs. 1b and 1d). The *Medium Center Offset* indicates 0.75 times the distance between the target and the center of the selection area of the *High Center Offset* (Figs. 1a and 1c).

We set the cut-off radius so that each target's selection area spanned 25° , a size commonly regarded as sufficient for gaze-based selection [Choi et al. 2022; Feit et al. 2017]. However, target density and the number of objects still differed by construction. In the *Cross* layout, the cut-off radius was set to 6.80° for both *Center Offset* levels. In the *Radial* layout, the cut-off radius was set to 5.65° when *Center Offset* was *Medium*, and to 6.80° when *Center Offset* was *High*. As a result, the distances between the centers of the target and the selection area were 1.5° for *Cross* $\times$ *Medium*, 2.0° for *Cross* $\times$ *High*, 3.4° for *Radial* $\times$ *Medium*, and 4.5° for *Radial* $\times$ *High*.

3.2 Feedforward Conditions for Comparison

We designed five types of visual feedforward: *Bubble*, *Outline*, *Cell*, *Label*, and *Icon* (Fig. 2). These feedforward types were adopted from previous studies [Baloup et al. 2019; Choi et al. 2020; Grossman and Balakrishnan 2005; Guillon et al. 2014, 2015; Huo et al. 2018; Mayer et al. 2020; Schenkluhn et al. 2024; Su et al. 2014]. Six visual feedforward conditions were compared, including the condition without any visual feedforward (*None*). In all conditions, the outline of the currently fixated object was highlighted in blue to indicate the user's gaze focus. The visualization parameters (e.g., color, transparency, outline width, icon size, and label text size) were determined through iterative refinement by the authors. The colors, transparency, and outline width were selected to reduce visual clutter, while label and icon sizes were set to ensure clear visibility while remaining small enough to avoid overlap with neighboring objects. The details of these visual feedforward are presented below:

- (1) **None** is the baseline condition, in which no visual feedforward is displayed [Baloup et al. 2019; Guillon et al. 2015; Su et al. 2014].
- (2) **Bubble** displays a 2D semi-transparent blue bubble cursor, which serves as a gaze cursor [Choi et al. 2020; Grossman and Balakrishnan 2005; Guillon et al. 2015]. When the user's gaze falls

within an object's selection area, the cursor's radius dynamically adjusts to fully encompass the object.

- (3) **Outline** visualizes the boundary of each object's selection area [Guillon et al. 2014, 2015]. The outline is blue, with a width of 0.006 m. When the user's gaze fixates on a selection area, its outline thickens to 0.02 m.
- (4) **Cell** visualizes each object's selection area [Guillon et al. 2014, 2015]. Each selection area is filled in with a semi-transparent gray color and outlined in blue with a width of 0.006 m. When the user's gaze fixates on a selection area, the filled area changes to a semi-transparent blue color.
- (5) **Label** displays a gray text label "Object" at the center of each object's selection area [Mayer et al. 2020]. Each text label is connected to its corresponding object by a gray line. The size of the text label is $0.24\text{ m} \times 0.07\text{ m}$ ($\approx 5.4^\circ \times 1.4^\circ$). When the user's gaze fixates on a selection area, the text label and line are highlighted in blue. If the text label overlapped with the object, it was repositioned to avoid the overlap.
- (6) **Icon** displays a gray circular icon with a white check mark at the center of each object's selection area [Huo et al. 2018; Schenkluhn et al. 2024]. Each icon is connected to its corresponding object by a gray line. The diameter of the icon is 3.0° . When a selection area is fixated upon, the icon and line are highlighted in blue.

To address RQ1, we primarily adopted visual feedforward conditions that alter the target's CoG (*Outline*, *Cell*, *Label*, and *Icon*). In addition, to examine the effects of CoG changes, we included the *Bubble*, which maintains a constant CoG. Although other visual feedforward methods exist, the following factors motivated our selection of these five conditions: (1) the limited number of conditions that could be implemented, (2) the goal of including multiple visual feedforward methods that involve CoG changes, and (3) prioritizing the *Bubble*, which has been shown to be effective for gaze-based interfaces [Choi et al. 2020], among methods that preserve the CoG.

3.3 Study Setup

3.3.1 Apparatus. We used the HTC Vive XR Elite HMD with the VIVE Full Face Tracker. The eye tracker of the HMD has an accuracy that ranges from 0.5° to 1.1° , a field of view of 110° , and a refresh rate of 90 Hz for both the HMD and the eye tracker. The HMD was used in stand-alone mode, using its pass-through feature. The application used in the study was developed in Unity 2022.3.21f1.

3.3.2 Design. We employed a within-participants design. There are three independent variables, as described earlier: (1) **Feedforward**: *None*, *Bubble*, *Outline*, *Cell*, *Label*, and *Icon*; (2) **Layout**: *Cross* and *Radial*; (3) **Center Offset**: *Medium* and *High*.

The order of the *Feedforward* conditions was counterbalanced using a Latin square design. Each participant completed two sessions per condition, with each session consisting of 32 trials ($2\text{ Layout} \times 2\text{ Center Offset} \times 8\text{ target positions}$). The eight target positions corresponded to the cardinal and intercardinal directions, defined relative to the center of the target's selection area in the *Cross* layout or relative to the center of all objects in the *Radial* layout. The order of the 32 trials within each session was randomized. We collected 384 valid trials per participant ($6\text{ Feedforward} \times 2\text{ sessions} \times 32\text{ trials}$), thereby yielding 6,912 trials across all 18 participants.

3.3.3 Task. The study task was to select a target using the dwell-time selection method. At the beginning of each trial, selectable objects were generated at positions defined by the *Layout* and *Center Offset* conditions. Each object was a sphere with an angular diameter of 1.0° , with the target colored red and all distractors colored white. The target was positioned 3.0 m in front of the

participant, and the remaining objects were arranged on a plane perpendicular to the participant's head direction. The visual feedforward was displayed at the same depth as its corresponding object.

An object was selected when the participant's gaze remained within its selection area for 0.7 s. To prevent unintended selections caused by involuntary fixation immediately after object generation, the dwell time within the first 0.3 s following object generation was ignored. The gaze data were processed using saccade detection [Feit et al. 2017] with a triangular kernel filter [Jimenez et al. 2008]. After a selection or a timeout of 5.0 s, the objects were regenerated. The target was regenerated at a random angular direction exactly 15° from the previous target, while remaining within a 20° radius centered on the participant's forward-facing direction. This sequence constituted a single trial.

3.3.4 Procedure. Upon arrival at the designated room in the local university, participants were seated 4.0 m from the wall and asked to read and sign an informed consent form. Thereafter, they completed a questionnaire collecting personal information, such as their name and gender. Subsequently, participants were provided an overview of the study, along with a detailed explanation of the selection area expansion algorithm and the characteristics of the visual feedforward. Participants who wore glasses were asked to remove them before putting on the HMD. The HMD's diopter and interpupillary distance were then adjusted, and the device was fitted to each participant. A five-point eye-tracking calibration was subsequently performed using the HMD's built-in software. Before the main task, all participants completed a practice session with different parameters to familiarize themselves with the procedure.

Each participant completed 32 trials per session and performed two consecutive sessions. This procedure was repeated for each of the six *Feedforward* conditions. After completing all trials, participants were interviewed and asked to indicate their preferred *Feedforward* conditions.

3.4 Metrics

We analyzed the following metrics:

Error rate (ER): The proportion of trials classified as errors. A trial was considered erroneous if a distractor was selected (false selection) or if no selection occurred within 5.0 s of trial onset (timeout).

Selection time (ST): The time from trial onset to successful target selection. The minimum ST was 1.0 s, thus reflecting the ignored 0.3 s dwell period to prevent unintended selections immediately after object generation and the 0.7 s dwell time required for selection.

Gaze offset (GO): The x-coordinate of fixation in a transformed 2D coordinate system in which the target was located at the origin and the selection-area center lay on the $+x$ axis. GO was converted to degrees of visual angle and analyzed only for non-timeout trials. For each trial, fixation was defined as the mean of gaze points recorded during the final 0.4 s of the 0.7 s dwell period. Values closer to zero indicate fixation positions along the x-axis closer to the target, whereas values closer to the distance between the target and the selection-area center indicate fixation positions closer to the selection-area center.

3.5 Results

Target selection failures occurred in 12.5% of all trials (861 out of 6,912). Among these error trials, timeouts accounted for 9.1% (78 out of 861). In addition, gaze data were not recorded for three trials, which were excluded from the analyses of ER, ST, and GO. The final number of valid data points was 6,909 for ER, 6,048 for ST, and 6,831 for GO.

For ER, we fitted a generalized linear mixed model (GLMM) [Bolker et al. 2009] with *Feedforward*, *Layout*, and *Center Offset* as fixed factors. The model was evaluated using Type-III Wald χ^2 tests. Post-hoc analyses were performed using pairwise comparisons of estimated marginal means, with

Table 1. Results of the GLMM for error rate (ER) and the ANOVA for selection time (ST) and gaze offset (GO) in Study 1. The variables *Feedforward*, *Layout*, and *Center Offset* are abbreviated as FFD, LAY, and CO, respectively.

Variable	Error Rate (ER)		Selection Time (ST)			Gaze Offset (GO)		
	χ^2 value	p	F value	p	η_p^2	F value	p	η_p^2
FFD	$\chi_5^2 = 97.22$	< .01	$F_{5,6008} = 2.18$	.05	.002	$F_{5,6790} = 200.99$	< .01	.129
LAY	$\chi_1^2 = 51.73$	< .01	$F_{1,6007} = 619.37$	< .01	.093	$F_{1,6790} = 842.75$	< .01	.110
CO	$\chi_1^2 = 35.03$	< .01	$F_{1,6007} = 88.34$	< .01	.014	$F_{1,6790} = 311.58$	< .01	.044
FFD $\times$ LAY	$\chi_5^2 = 11.23$	< .05	$F_{5,6007} = 2.58$	< .05	.002	$F_{5,6790} = 69.29$	< .01	.049
FFD $\times$ CO	$\chi_5^2 = 5.94$	.31	$F_{5,6007} = 0.99$	.42	.001	$F_{5,6790} = 10.56$	< .01	.008
LAY $\times$ CO	$\chi_1^2 = 5.81$	< .05	$F_{1,6007} = 15.35$	< .01	.003	$F_{1,6790} = 79.17$	< .01	.012
FFD $\times$ LAY $\times$ CO	$\chi_5^2 = 16.02$	< .01	$F_{5,6007} = 0.53$	.75	.000	$F_{5,6790} = 7.16$	< .01	.005

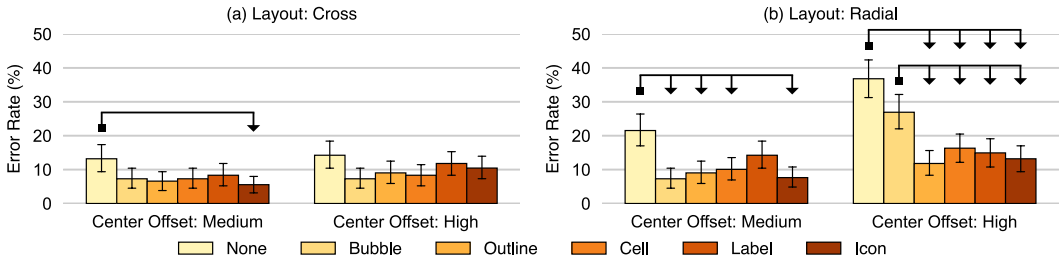


Fig. 3. Error rate (ER) for (a) the *Cross* layout and (b) the *Radial* layout. Error bars represent 95% confidence intervals. Statistically significant differences ($p < .05$) are indicated by solid lines connecting the square (■) and triangle (▼) markers.

Tukey correction. For ST and GO, we found that the data were not normally distributed. Therefore, we applied the aligned rank transform [Wobbrock et al. 2011] to each dataset, followed by a three-way repeated measures ANOVA with *Feedforward*, *Layout*, and *Center Offset* as within-subject factors. Subsequently, we performed ART-C [Elkin et al. 2021] with Holm correction [Holm 1979] for post-hoc analysis. The results of the GLMM and ANOVA are summarized in Table 1.

3.5.1 Error Rate (ER). Fig. 3 depicts the ER across *Layout* and *Center Offset* values for each *Feedforward* condition. The ERs were 21.44% for *None*, 12.17% for *Bubble*, 9.11% for *Outline*, 10.50% for *Cell*, 12.32% for *Label*, and 9.21% for *Icon*. In the *Radial Layout*, *Bubble*, *Outline*, *Cell*, and *Icon* showed significantly lower ERs than *None* in the *Medium Center Offset* condition; *None* showed significantly higher ERs than the other *Feedforward* conditions in the *High Center Offset* condition. Although *Bubble* reduced the overall ER compared to *None*, it still produced significantly higher ERs than the other feedforward conditions in the *Radial Layout $\times$ High Center Offset* condition.

3.5.2 Selection Time (ST). The median STs were 1.36 s for *None*, 1.36 s for *Bubble*, 1.36 s for *Outline*, 1.39 s for *Cell*, 1.39 s for *Label*, and 1.41 s for *Icon*. In the *Cross Layout*, the *Outline* condition (median = 1.21 s) resulted in significantly faster STs than the *Icon* condition (median = 1.30 s) ($t_{6007} = 3.49$, $p < .05$). However, in terms of effect sizes, the main contributing factors for ST were *Layout* ($\eta_p^2 = .093$) and *Center Offset* ($\eta_p^2 = .014$), while the effect of *Feedforward* was relatively small ($\eta_p^2 = .002$).

3.5.3 Gaze Offset (GO). Fig. 4 depicts the GO, and Fig. 5 illustrates the 95% confidence ellipses of fixations across *Layout* and *Center Offset* values for each *Feedforward* condition. The *None* and *Bubble* conditions revealed significantly smaller GOs than the other feedforward conditions. These

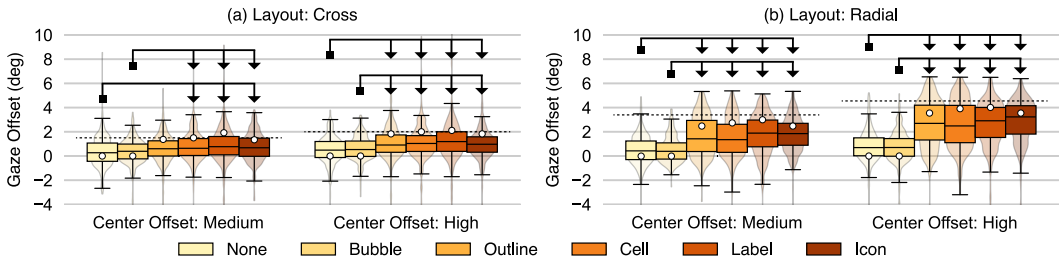


Fig. 4. Gaze offset (GO) for (a) the *Cross* layout and (b) the *Radial* layout. The dashed lines indicate the centers of the selection areas, and the circles (o) represent the visual-space CoGs of the targets. Statistically significant differences ($p < .05$) are shown by solid lines connecting the square (■) and triangle (▼) markers.

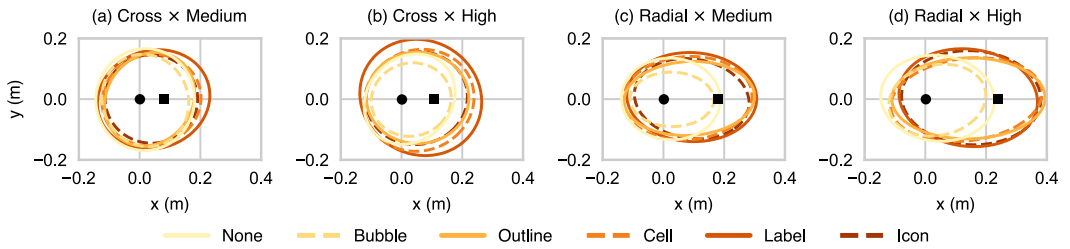


Fig. 5. 95% confidence ellipses of the fixations. The circles (●) represent the target positions, and the squares (■) represent the center of the selection areas.

results indicate that the *Bubble* condition directs participants' gaze to the center of the target, whereas the *Outline*, *Cell*, *Label*, and *Icon* conditions successfully guided the participants' gaze toward the center of the selection area.

3.5.4 Participants' Feedback. The weighted average preference rankings were 3.95 for *None*, 2.14 for *Bubble*, 2.52 for *Outline*, 2.42 for *Cell*, 3.33 for *Label*, and 3.62 for *Icon*. Accordingly, *Feedforward* conditions were ranked from most to least preferred in the following manner: *Bubble* > *Cell* > *Outline* > *Label* > *Icon* > *None*.

For the *None* condition, most participants expressed dissatisfaction with the higher error rate. However, three participants appreciated the *None* condition for its lack of visual distraction. For the *Bubble* condition, participants preferred visualizing the gaze cursor, as it helped them adjust their gaze position more accurately. P14 commented, "Because I could see where I was looking, it was easy to correct my gaze when I was about to make a wrong selection."

For the *Outline* condition, participants tended to direct their gaze toward the center of the selection area rather than at the target, influenced by the visualization of the selection area's outline (P15: "By focusing on the selection area rather than the target, it became easier to make selections."). P6 and P14 reported adjusting their fixation positions to take advantage of the outline visualization (P6: "I made selections by focusing on the periphery of the selection area, away from the target."). For the *Cell* condition, the visualization of the selection area also enabled participants to direct their gaze toward the center of the selection area. However, P9 found the large, filled selection area in their field of view to be visually overwhelming ("It would have been better without the fill, as it made the background difficult to see.").

For the *Label* condition, participants believed that their gaze was naturally drawn to the text labels (P7: “My gaze went to the text more than I expected.”). However, several participants also reported that the horizontally arranged text labels increased visual clutter. P15 noted, “When a target’s text label was near a distractor, that distractor was more likely to be selected by mistake.” For the *Icon* condition, participants believed that the icon guided their gaze (P18: “Similar to the *Label* condition, I tended to look at the icon instead of the target.”). However, several participants reported that the large icons were visually distracting (P1: “The icons were so large that they obstructed my view.”) and expressed confusion regarding whether to focus on the target or the icon (P5: “I was unsure whether I should look at the target or the icon.”).

3.6 Summary of Study 1

We investigated target selection performance under six visual feedforward conditions. Compared with the *None* condition, the *Outline*, *Cell*, *Label*, and *Icon* conditions shifted fixations toward the center of the selection area, thereby significantly improving selection accuracy. By contrast, the *Bubble* condition could not guide gaze toward the center of the selection area, and fixations were distributed around the center of the target. Nevertheless, it was the most preferred feedforward condition and effectively reduced the error rates across all conditions, except *Radial* $\times$ *High*.

4 Study 2

Based on the results of Study 1, we observed that the *Bubble* condition improved selection accuracy without shifting fixation toward the selection-area center, which was unexpected. We hypothesized that this improvement stemmed primarily from visualizing gaze position rather than from the bubble mechanism itself, and that adding a gaze cursor to other feedforward types could further enhance selection accuracy. To test these hypotheses, we conducted a follow-up study. This study was also approved by the ethics review committee of our institute (number 2024R866).

Twenty-four participants (8 female and 16 male; mean age = 23.3 years, $SD = 1.4$, IDs: 19–42) were recruited from a local university. All participants had normal color vision. Among them, five had normal vision, ten wore glasses, and nine wore contact lenses. Additionally, four participants had prior experience with gaze-based interfaces. Each participant received US\$12 as compensation, and each session lasted approximately 70 minutes.

4.1 Study Setup

We employed a within-participants design. There are three independent variables: (1) **Feedforward**: *None*, *Bubble*, *Outline*, *Cell*, *Label*, and *Icon*; (2) **Layout**: *Cross* and *Radial*; (3) **Gaze Cursor**: *Off* and *On*.

The *Feedforward* and *Layout* conditions were identical to those used in Study 1. The *Gaze Cursor* factor indicated whether a gaze cursor was visible. The gaze cursor was represented by a yellow circle with a diameter of 0.5° , positioned 2.9 m from the participant’s head. In the *Bubble* condition, when *Gaze Cursor* was *On*, the yellow circle was not displayed; instead, a blue bubble cursor—identical to that used in Study 1—served as the gaze cursor. When *Gaze Cursor* was *Off*, the gaze cursor was invisible. That is, the *None* $\times$ *Off* and *Bubble* $\times$ *Off* conditions had identical visual appearances to the *None* condition in Study 1, and they also shared the same selection logic and definition of the selection area.

The orders of the *Feedforward* and *Gaze Cursor* conditions were counterbalanced, with the former following a Latin square design. Each participant experienced both *Gaze Cursor* conditions sequentially for each *Feedforward* condition. The *Gaze Cursor* condition was alternated each time a new *Feedforward* condition was introduced. Half of the participants began their first *Feedforward* condition under the *Off* condition, while the other half began under the *On* condition. Participants

Table 2. Results of the GLMM for error rate (ER) and the ANOVA for selection time (ST) and gaze offset (GO) in Study 2. The variables *Feedforward*, *Layout*, and *Gaze Cursor* are abbreviated as FFD, LAY, and GC, respectively.

Variable	Error Rate (ER)			Selection Time (ST)			Gaze Offset (GO)		
	χ^2 value	p		F value	p	η_p^2	F value	p	η_p^2
FFD	$\chi^2_5 = 152.96$	< .01		$F_{5,7556} = 2.47$	< .05	.002	$F_{5,8983} = 240.62$	< .01	.118
LAY	$\chi^2_1 = 143.38$	< .01		$F_{1,7556} = 1013.31$	< .01	.118	$F_{1,8983} = 847.99$	< .01	.086
GC	$\chi^2_1 = 60.32$	< .01		$F_{1,7555} = 0.13$	.72	.000	$F_{1,8983} = 7.86$	< .01	.001
FFD $\times$ LAY	$\chi^2_5 = 44.94$	< .01		$F_{5,7554} = 0.57$	.73	.000	$F_{5,8983} = 63.40$	< .01	.034
FFD $\times$ GC	$\chi^2_5 = 9.24$	.10		$F_{5,7555} = 3.98$	< .01	.003	$F_{5,8983} = 0.44$	.82	.000
LAY $\times$ GC	$\chi^2_1 = 0.31$	.58		$F_{1,7554} = 1.18$	.28	.000	$F_{5,8983} = 2.86$	.09	.000
FFD $\times$ LAY $\times$ GC	$\chi^2_5 = 12.32$	< .05		$F_{5,7554} = 1.42$	.21	.001	$F_{5,8983} = 0.64$	.67	.000

completed two sessions of 16 trials (2 *Layout* $\times$ 8 target positions) for each combination of *Feedforward* and *Gaze Cursor*. The order of the 16 trials within each session was randomized. We collected 384 valid trials per participant (6 *Feedforward* $\times$ 2 *Gaze Cursor* $\times$ 32 trials), thereby yielding 9,216 trials across all 24 participants.

The apparatus, procedure, task, and metrics were identical to those used in Study 1. The objects were generated with a *Center Offset* set to the *High* condition. After completing all trials for a given *Feedforward* condition, the participants were asked to indicate their preferred *Gaze Cursor* condition. This process was repeated for all six *Feedforward* conditions. After completing all trials, participants were interviewed and asked to report their preferred *Feedforward* condition.

4.2 Results

Target selection failures occurred in 17.5% of all trials (1,612 out of 9,216). Among these error trials, timeouts accounted for 11.4% (183 out of 1,612). In addition, gaze data were not recorded for three trials, which were excluded from the analyses of ER, ST, and GO. The final number of valid data points was 9,213 for ER, 7,601 for ST, and 9,030 for GO.

For ER, ST, and GO, we employed the same statistical procedures as those in Study 1, using *Feedforward*, *Layout*, and *Gaze Cursor* as within-subject factors. The results of these analyses are summarized in Table 2.

4.2.1 Error Rate (ER). Fig. 6 depicts the ER across *Feedforward* and *Layout* values for each *Gaze Cursor* condition. In the *Cross Layout*, the *None*, *Bubble*, and *Cell* conditions significantly reduced ERs when the gaze cursor was visualized. In the *Radial Layout*, the *None*, *Cell*, *Label*, and *Icon* conditions also showed significant reductions in ERs when the gaze cursor was visualized. These results suggest that visualizing the gaze cursor can enhance selection accuracy when combined with other forms of visual feedforward.

4.2.2 Selection Time (ST). In the *Outline* condition, displaying the gaze cursor resulted in significantly faster STs (median: 1.43 s vs. 1.52 s) ($t_{7555} = 3.38$, $p < .05$). However, in terms of effect size, the main contributing factor to ST was *Layout* ($\eta_p^2 = .118$), whereas the *Feedforward* $\times$ *Gaze Cursor* interaction revealed only a minimal effect ($\eta_p^2 = .003$).

4.2.3 Gaze Offset (GO). A significant main effect was observed for *Gaze Cursor*. Post-hoc analysis of the interaction involving *Gaze Cursor* revealed no significant differences. Overall, displaying the gaze cursor (median = 1.00°) resulted in significantly smaller GOs than not displaying it (median = 1.15°).

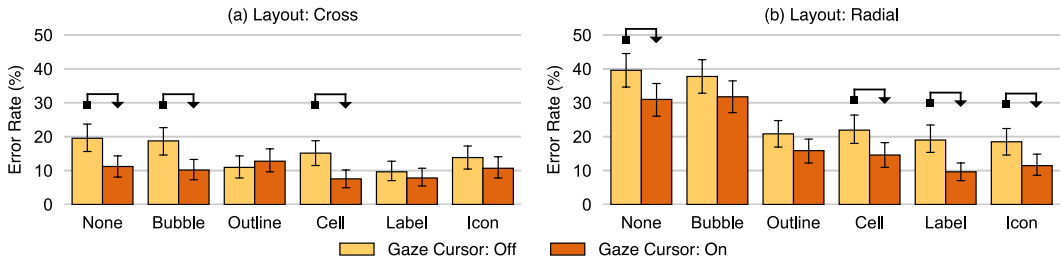


Fig. 6. Error rate (ER) for (a) the *Cross* layout and (b) the *Radial* layout. Error bars represent 95% confidence intervals. Statistically significant differences ($p < .05$) are indicated by solid lines connecting the square (■) and triangle (▼) markers.

4.2.4 Participants' Feedback. The weighted average preference rankings for *Feedforward* were 5.29 for *None*, 3.95 for *Bubble*, 3.76 for *Outline*, 2.95 for *Cell*, 3.76 for *Label*, and 4.29 for *Icon*. Accordingly, *Feedforward* conditions were ranked from most to least preferred in the following manner: *Cell* > *Outline* = *Label* > *Bubble* > *Icon* > *None*.

With regard to participants' preferences for the *Gaze Cursor* across *Feedforward* conditions, displaying the gaze cursor was preferred in all cases. The following proportion of participants preferred the *On* condition: *None*—75% (18/24), *Bubble*—75% (18/24), *Outline*—92% (22/24), *Cell*—67% (16/24), *Label*—71% (17/24), and *Icon*—63% (15/24).

Further, the gaze cursor was used to identify discrepancies between participants' actual gaze and the system's estimated gaze position, thereby enabling them to make adjustments accordingly. P33 commented, "Because the gaze cursor drifted to the left, I moved my gaze or head slightly to the right of the target." By contrast, a few participants reported that displaying both the selection area (or its center) and the gaze cursor created visual clutter. Under the *Label* condition, P22 commented, "I would have preferred no cursor, as there was too much visual information."

4.3 Summary of Study 2

We investigated selection performance under six visual feedforward conditions, both with and without a display of the gaze cursor. The condition with the gaze cursor showed significantly lower GO values than the condition without it. However, in the *Radial* layout, combining the gaze cursor with the *Cell*, *Label*, or *Icon* feedforward conditions significantly improved selection accuracy compared to conditions without the gaze cursor. Moreover, participants preferred the conditions with the gaze cursor across all *Feedforward* conditions.

5 Discussion

5.1 RQ1: Alteration of Fixation Position via Visual Feedforward

The results of Studies 1 and 2 demonstrated that visualizing the selection area or its center effectively guided users' fixations toward the center of the selection area. By contrast, when visual feedforward displayed a gaze cursor, fixations tended to remain closer to the target itself. These findings suggest that users' gaze can be guided toward the center of the selection area by altering the target's visual-space CoG through visual feedforward.

However, when visual feedforward altered the visual-space CoG, fixations were broadly distributed between the visual-space CoG and the target's CoG (Fig. 5). This result contrasts with those of previous studies that report that humans tend to fixate on an object's visual-space CoG [Melcher

and Kowler 1999]. This may be because participants have perceived the target itself as more important visual information to focus on than the visual feedforward. Prior research has revealed that fixations tend to land on functionally relevant object parts [van der Linden et al. 2015]. Thus, participants perceived the *center of mass* as being shifted toward the target, leading to a corresponding shift in fixation.

Further, the studies revealed that changing the visual-space CoG alters fixation positions, thereby suggesting the potential to guide users' gaze toward desired locations through visual feedforward. This demonstrates that it is possible to adopt an approach in which the system actively guides users' gaze toward locations where it can more reliably infer their intended target rather than solely relying on gaze target estimation. Theoretically, since gaze estimation accuracy will never be perfect [MacKenzie 2010], designing user interfaces that enable systems to more easily interpret users' focus of attention—as in the approach proposed in this study—is crucial for advancing gaze-based interaction.

5.2 RQ2: Selection Performance for Each Visual Feedforward

We confirmed that visual feedforward conditions that visualize the selection area or its center and those that display a gaze cursor both improved selection accuracy; moreover, combining these visual feedforward methods led to additional improvements. These mechanisms appear to enhance selection accuracy through different strategies, indicating that their combination can efficiently improve selection precision.

Visual feedforward that displays a gaze cursor (*Bubble*) was the most preferred condition among participants in Study 1 and also improved selection accuracy. Participants used the cursor to identify discrepancies between their intended gaze and the system's estimated gaze position, and adjusted their gaze accordingly to align the cursor with the target better, thereby improving accuracy. This user-driven gaze-cursor adjustment strategy for non-expanded object selection has also been reported in previous research [Wei et al. 2025]. Our results further suggest that this strategy can also be applied to expanded selection areas when using the dwell-time selection method.

Although altering a target's CoG improved selection accuracy across all *Layout* $\times$ *Center Offset* conditions, displaying a gaze cursor did not improve selection accuracy in the *Radial Layout* $\times$ *High Center Offset* condition. In this condition, the distance between the target center and the selection-area center was the greatest, and there was little margin in the selection area surrounding the target. Consistently, the error rates were higher in the *Radial Layout* than in the *Cross Layout*, indicating that the *Radial Layout* is more sensitive to gaze divergence when margins are small. Thus, when fixating the selection-area center is critical, a gaze cursor alone provides limited benefit.

5.3 Appropriate Use of Visual Feedforward

When applying selection-area expansion using Voronoi tessellation, the choice of visual feedforward should consider both the expected improvement in selection accuracy and the degree of visual distraction. In our tested settings, the highest selection accuracy was typically achieved by combining a feedforward that visualizes the selection area (or its center) with displaying a gaze cursor. However, this combination also increased visual distraction, and Study 2 confirmed that some participants preferred conditions without a gaze cursor. Thus, when high-precision selection is required, particularly in high-density environments, we recommend this combined approach.

Although visualizing the selection area or its center improved selection accuracy to a similar extent, the types of visual distraction differed across conditions. Participant comments indicated that visualizing the center of the selection area was less preferred because text labels and icons were visually distracting. In addition, some participants reported visual clutter in the *Cell* condition. Visual noise should be minimized as much as possible; therefore, discrete feedforward approaches [Guillon

et al. 2015], such as visualizing only the selection area of the currently gazed object, should be considered. Although this approach may increase selection times, it may be more practical because it reduces UI clutter.

While the benefit of a gaze cursor was limited in high-density settings, it improved selection accuracy with minimal additional visual distraction in other contexts. The *Bubble* condition is the only feedforward type with a cursor that changes shape continuously, whereas the other feedforward conditions are static in form. Nevertheless, our results suggest that *Bubble*'s gain stems primarily from visualizing gaze position rather than from its dynamic shape. Because bubble cursors can expand dynamically (up to the cut-off radius in our setup), they may become overly salient and visually distracting, reflecting a trade-off between feedforward saliency and UI clutter. Thus, we recommend using a simple point cursor. Furthermore, compared with visualizing the selection area or its center, gaze cursors typically incur lower computational overhead, as they do not require calculating or rendering the outline of the selection area. This makes them suitable for systems that require lightweight processing or operate under limited computational resources.

5.4 Limitations

This study has several limitations. First, there are limitations related to participant demographics. Most participants were in their early twenties, and the gender distribution was skewed (32 of 42 identified as male). In Study 1, participants were primarily recruited from our VR/MR research laboratory, which may limit the generalizability of the findings. In addition, half of the participants in Study 1 (9 of 18) had prior experience with gaze-based interfaces, a proportion notably higher than that in Study 2 (4 of 24). This prior experience may have influenced performance and may partly explain the lower error rate observed in Study 1 compared with Study 2.

Second, this study exclusively focused on situations where the centers of the target and the selection area were misaligned, and did not examine cases in which they coincided. Third, only two layout types—*Cross* and *Radial*—were investigated. Fourth, visual feedforward was evaluated only in a simple object-selection task; therefore, its effectiveness for selecting complex-shaped objects and the potential effects of visual clutter remain unclear. Finally, this study employed a within-participants design, which may have introduced carryover effects due to participants' prior knowledge of the selection area's shape or center position, potentially influencing the results.

6 Conclusion

In this study, we investigated whether visual feedforward can enhance selection performance in gaze-based interfaces when selection areas are expanded using Voronoi tessellation. The results revealed that visualizing the selection area or its center guided users' fixations toward the center of the selection area, thereby improving selection accuracy. In addition, displaying a gaze cursor further enhanced selection accuracy, with the most effective feedforward reducing error rates by up to 75.8%. These findings emphasize the importance of appropriate visual feedforward design and highlight the role of considering a target's visual-space CoG when developing gaze-based interaction techniques.

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