Efficient Eye Pointing with a Fisheye Lens

Michael Ashmore, Andrew T. Duchowski
Department of Computer Science, Clemson University
Clemson, SC, USA

Garth Shoemaker
Idelix Software Inc.
Vancouver, BC, Canada

Abstract

This paper evaluates refinements to existing eye pointing techniques involving a fisheye lens. We use a fisheye lens and a video-based eye tracker to locally magnify the display at the point of the user's gaze. Our *gaze-contingent* fisheye facilitates eye pointing and selection of magnified (expanded) targets. Two novel interaction techniques are evaluated for managing the fisheye, both dependent on real-time analysis of the user's eye movements. Unlike previous attempts at gaze-contingent fisheye control, our key innovation is to hide the fisheye during visual search, and morph the fisheye into view as soon as the user completes a saccadic eye movement and has begun fixating a target. This style of interaction allows the user to maintain an overview of the desktop during search while selectively zooming in on the foveal region of interest during selection. Comparison of these interaction styles with ones where the fisheye is continuously slaved to the user's gaze (omnipresent) or is not used to affect target expansion (nonexistent) shows performance benefits in terms of speed and accuracy.

Key words: Eye Pointing, Fisheyes

1 Introduction

As real-time indicators of a user's gaze, eye trackers hold potential for allowing the eye to act as a pointing device. According to Zhai et al. [29], this may seem unnatural as loading of the visual perception channel with a motor control task seems fundamentally at odds with users' natural mental model in which the eye searches for and takes in information, while coordinating with the hand for manipulation of external objects. Nevertheless, real-time eye pointing and selecting of interface objects is at once both important and desirable for its myriad of potential uses. Eye pointing has assisted users with severe motor disabilities, e.g., quadriplegics, allowing them to communicate by typing with their eyes [16]. Eye pointing has also been considered for its general interactive benefits, with applications ranging from basic vision research [5], computer-mediated communication in virtual reality [6], and human-computer interaction in the form of Attentive User Interfaces, or AUIs [25], among others.

Unfortunately, eye pointing is inherently more problematic than manual pointing for the following reasons:

1. *Eye tracker accuracy.* It is generally accepted that the accuracy of current eye tracking technology is limited to about 0.5-1° visual angle. This implies that when viewing a typical 17″ computer monitor at a viewing distance of 50 cm, eye pointing is limited in accuracy to about 16-33 pixels due to eye tracker error (assuming a 1280×1024 or 96 dpi resolution display).

2. *Sensor lag.* As with most motion tracking systems, the eye tracker incurs a delay in processing gaze position. For camera-based corneal reflection eye trackers (the current choice for unobtrusive tracking) the delay generally depends on the frame rate of the camera used to image the eye. The real-time lag of current trackers ranges anywhere from 5-33 milliseconds (200-30 Hz frame rates).

3. *Fixation jitter.* Although eye pointing is typically associated with prolonged dwell (fixation), this type of eye movement is never perfectly stationary and exhibits jitter. Unlike a mouse that can be released to output a constant coordinate, at least three types of small, involuntary eye movements perturb fixations [1]: *flicks*, rapid (perhaps as quick as 30 ms apart), involuntary, saccade-like motions of less than 1°; *drifts*, small, slow (about 0.1°/s), apparently random motions of the eye; and *tremors*, tiny (< 30 arc seconds), high frequency (30-150 Hz) eye vibrations.

4. *Midas touch.* This well-known problem, described by Jacob [12], makes target selection by gaze ambiguous due to the involuntary aspects of certain eye movements and behaviours. For example, since target selection by gaze necessitates looking at the target, ambiguity arises from the user looking at many targets in rapid succession. Should all targets be activated by a mere glance (e.g., turn to gold in the Midas analogy)? Using blinks does not disambiguate target selection since not all blinks are voluntary.

Various solutions have been proposed to address these challenges. Technological advancements in computer vision, for example, are improving accuracy and removing the need for calibration [13]. Signal analysis for eye movement prediction can offset sensor lag. Fixation jitter can be smoothed by real-time filtering at the expense of a slight processing delay. The solution to the Midas touch problem can involve dwell time, e.g., fixating a target for an appreciable period of time, say 500 ms, or an auxiliary mechanism for activation of targets selected by gaze, e.g., mouse clicks [29, 7]. Dwell time is possibly the most common mechanism used to disambiguate target selection by gaze.

Despite ongoing research efforts and steadily improving technology, eye pointing is difficult, especially for the disabled, for whom specialized interfaces are often developed [11]. Generally, such interfaces are designed with oversized targets (e.g., virtual keyboards [16]) to facilitate selection with gaze.

In this paper, we evaluate the use of the fisheye lens in two novel interactive ways for the purpose of eye pointing. First, we design a fisheye that is only engaged after the viewer begins fixating a target. This type of fisheye allows an overview of the screen prior to making a selection. This first interaction style is similar in spirit to Zhai et al.'s MAGIC pointing [29]. Unlike MAGIC pointing, where the MAGIC cursor was warped to the vicinity of one's gaze prior to mouse movement, in this case the lens, and hence the eye cursor, is directly slaved to gaze position, with its appearance modulated by real-time fixation estimation (and not predicted direction of eye movement). The lens therefore "magically" appears just when it is needed.[1] Second, we evaluate a variation of the first technique by fixing the lens in place following its appearance after fixation onset. This interaction style is similar to the grab-and-hold algorithm (GHA) developed by Miniotas and Špakov [20] to counteract fixation jitter. That is, once the lens is made visible, it is fixed in place and the eye pointer is now free to move within the lens region. As soon as the eye moves sufficiently quickly and far away from the first fixation (a saccade is detected), the lens disappears again.

We compare these two fisheye interactions to both a nonexistent fisheye (the control condition) and to an omnipresent (always-on) fisheye slaved to the user's gaze. The "Nonexistent" condition simply means the user must select targets without the aid of a fisheye lens. Conversely, the "Omnipresent" condition is one where the lens is always visible and continuously slaved to the user's gaze. In all cases, the user must select a target via dwell time, i.e., by fixating the target. Criteria for dwell time selection is the same in all cases (see Methodology below).

2 Background

Eye pointing is, in principle, similar to manual pointing, although the debate regarding its predictability by Fitts' Law complicates this metaphor. If Fitts' Law were a suitable model, then any innovations developed for manual interaction could potentially transfer to eye pointing. Ware and Mikaelian [27] found that eye input does indeed follow Fitts' Law, although Zhai et al. [29] reported only low correlation to the model ($r^2 = .75$). More recently, Miniotas [19] reported fairly high correlation ($r^2 = .98$) with the following Fitts' variation, expressing mean selection time (MT) as: $MT = a + b \log_2 (A/W + 0.5)$, with $a = 298$ (ms) and $b = 176$ (ms/bit).

Whatever the specific Fitts' Law model for eye pointing may be, the sentiment embodied by the law intuitively carries over from manual input. Specifically, the law predicts reduced mean selection time via either reduction of target distance or by expansion of target size, or a combination of both. Several techniques for expanding target size have been developed for both eye and mouse pointing:

- expand the target (invisibly) strictly in motor space,
- expand (zoom into) the entire display uniformly, or
- expand a portion of the screen through a fisheye lens.

Bates and Istance demonstrated an eye mouse system with a full-screen zoom facility and showed improvement in eye mouse performance to a level competitive with head-controlled pointing devices [2]. One of the disadvantages of full-screen zooming, however, is the loss of contextual information: information outside the zoomed region is lost. This loss can be problematic for interaction, as addressed by Baudisch et al.'s [3] focus plus context screens.

Loss of contextual (preview) information is particularly problematic for tasks involving visual search [8]. Therefore, localized target expansion seems to be a logical alternative for decreasing selection time. Zhai et al. [28] found that target expansion can increase pointing speed and accuracy with conventional input devices. Miniotas et al. have shown that target expansion also increases eye pointing speed and accuracy [21]. Their experimental paradigm closely followed that of Zhai et al., with target expansion performed strictly in motor space (i.e., invisible to the user). They did not investigate eye pointing for multiple expanding targets that are close together.

---

[1]Perhaps a more appropriate characterization of our eye pointing incarnation may be: Motion Analyzed Gaze Input Cursor (MAGIC) pointing.

An alternative to both target expansion in motor space and global zooming can be obtained with a fisheye lens, provided targets are expanded both in display and motor space. Otherwise, as McGuffin and Balakrishnan [18] observed, fisheyes provide no pointing advantage since even though the fisheye view enlarges targets in display space, it makes no difference in motor space. Zooming within display space magnifies a small portion of the display. Targets that are close together are magnified and separated. Since fisheyes are usually smaller than the display, context information is preserved, and therefore, according to Gutwin and Skopik [10], fisheyes are well-suited to steering tasks.

Unfortunately, due to their distortive projection of the display space, fisheyes have been found to have an adverse effect on targeting tasks with input devices such as handheld mice and trackballs [9]. The "Gutwin effect", to coin the term, describes the problematic apparent motion of objects within the lens' field of view in a direction opposite to that of the lens. For instance, as the lens is moved to the right, objects below the lens appear to move to the left at a magnified velocity. The Gutwin effect poses additional problems for gaze controlled fisheyes (see below).

There seems to be scant evaluation of fisheyes for eye pointing tasks. Our early anecdotal observations with gaze-contingent fisheyes exposed two major difficulties, motivating our design of the MAGIC and GHA style lenses:

1. Lens oscillation: when continuously slaved to the point of gaze, the fisheye rocks back and forth during eye selection, an effect we believe to be a source of considerable frustration to users. Lens oscillation appears to worsen in direct proportion to the user's increased effort at controlling lens position. We believe this effect arises from a combination of factors inducing a positive feedback loop between the application and the user's visual system. The processing lag in gaze point calculation coupled with the Gutwin effect compels the user to issue correctional eye movements thereby overcompensating the eye-slaved lens position. Because eye movements are faster than manual movements, we believe this effect is more pronounced and disturbing under gaze control than under manual control. Lens oscillations can generally be reduced by attenuating control gain (see Methodology below).

2. Lack of preview benefit: manual fisheyes may be effective for steering tasks, however, in such tasks the eyes are free to look ahead down the path that the manual pointing device is to follow. That

is, "look-ahead" eye movements generally precede hand movements [22]. Slaving a fisheye lens to one's point of gaze prevents these eye movements and robs the viewer from determining future eye movement and hence fisheye direction. That is, while the fisheye preserves peripheral context, this information can only be processed by the periphery of the retina at reduced resolution. To process the information at high resolution by the fovea, one has to be able to look beyond the center of the lens. A continuously eye-slaved fisheye makes this impossible.

The closest related work appears to be that of Vertegaal [26] who investigated gaze-controlled fisheyes and then applied his patent pending technology to the contraction/expansion of non-overlapping "elastic" windows [7]. The similarity of these approaches lies in the use of dwell time for zoom activation. Fono and Vertegaal's display, however, was markedly different from the visual appearance of our fisheye lens. Specifically, their zooming effect was achieved through minification of peripheral windows, preserving the focal window at original resolution. The effect was applied globally, distorting the entire display. In contrast, our fisheye magnifies the display locally at the lens center, preserving peripheral resolution without minification. To our knowledge, prior evaluation of the fisheye lens for eye pointing has not been performed.

3 Methodology

The fisheye lens library we use for the experiment, Pliable Display Technology, or PDT, based on the work of Carpendale et al. [4] and available commercially from Idelix Software,[2] allows local magnification of data while keeping a continuous visual connection to the underlying display. The lens relies on a geometric transform of *data space* to *display space* through a pliable or elastic mesh surface enabling content to be stretched from below the surface with lenses of the appropriate height, volume, and shape. Matching data space resolution to magnification factor allows simultaneous target expansion in motor and display space.

To evaluate fisheye interaction for eye pointing, we devised a combined visual search and Fitts' Law pointing task with randomly variable target distance (amplitude) and fixed target width (when not magnified by the fisheye).

3.1 Experimental Design

A within-subjects, repeated measures 4-factorial design was employed in the study with the following fisheye interaction conditions:
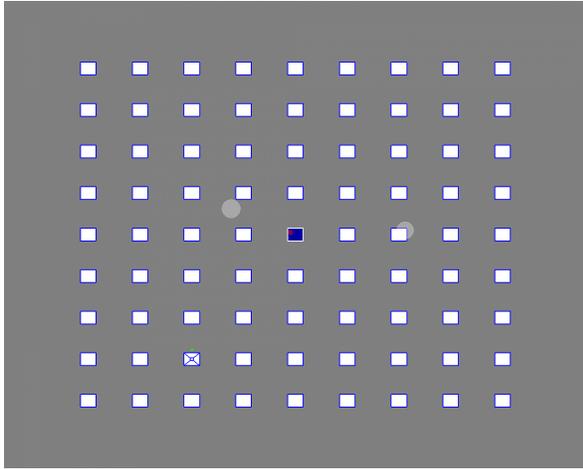
Figure 1: Experimental setup (non-fisheye condition) indicating fixated central home position target with the next target visible at bottom left. The two translucent disks indicate the camera's view of the user's eyes.
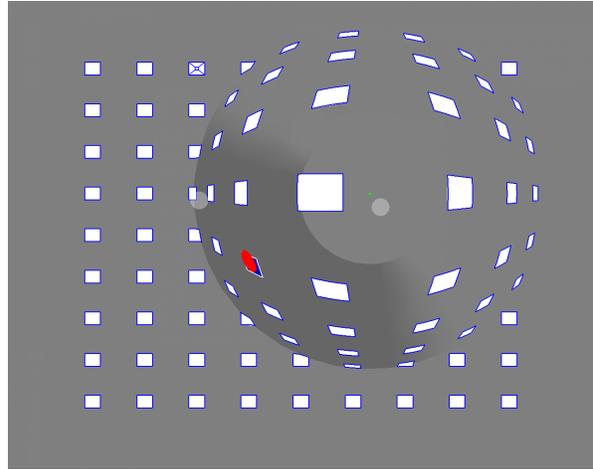

Figure 2: The user interface. The lens' central (foveal) region's diameter covers 20% of the screen's width with the lens shoulder extending the lens' diameter to 60% of screen width.

1. Nonexistent (control condition),
2. Omnipresent (always-on),
3. MAGIC, appearing only after fixation onset, and
4. GHA (Grab and Hold Algorithm), as with MAGIC but fixed in place once visible after fixation onset.

A Latin square was used to counterbalance the order of interaction style presentation to reduce learning or fatigue effects.

3.2 Hypothesis

We hypothesize that at least one of the MAGIC or GHA fisheyes will provide speed and accuracy benefits for eye pointing compared to the cases of continuously eye-slaved fisheye or no fisheye at all. We believe the efficiency benefit will derive from the preservation of preview benefit during visual search, and, in the case of the GHA lens, from addressing the Gutwin effect through cessation of lens motion.

3.3 Display

To combine visual search with a Fitts' Law task, a 9×9 grid of target boxes serves as the targeting stimulus. At 1280×1024 (∼96 dpi) resolution and 50 cm viewing distance (best operating range of the eye tracker), when not magnified in *display space*, each box subtends ∼1.3° visual angle on the diagonal (34×27 pixels). Target boxes are defined 3 times as large in *data space* and appear at this resolution under magnification. The stimulus display (no magnification) is shown in Figure 1. Target boxes occupy 80% of the screen with 10% screen space occupied by each margin. In normalized screen coordinates, the distance between target box centers is 0.8/9, i.e., for the

1280×1024 screen, $0.8(1280)/9 = 113.8$ pixels ($\sim3.4°$) horizontally, and $0.8(1024)/9 = 91.0$ pixels ($\sim2.8°$) vertically.

Unlike Miniotas et al.'s previous study [21], two key forms of visual feedback are provided to the user. First, a green gaze dot (eye pointer) is drawn at the user's point of regard. Second, the camera's view of the user's eyes are depicted by two translucent disks (shown slightly tilted in Figure 1). These disks serve as indicators of the user's head position relative to the eye tracker's camera. Should the user shift their head out of camera view, one (or both) disks would disappear. Users are typically instructed to maintain these disks at mid-screen level height. If the user moves their head out of the working range of the camera, the eye tracker pauses operation and resumes once the user's eyes are once again visible to the camera. Although we did not record precise occurrences of these pauses, they did not seem to pose problems to any users.

Animation feedback for eye targeting and selection is provided by first marking the target box with a large × through its center. Target selection is achieved following a 500 ms fixation (dwell time) within the box boundaries in *display space* (snap-to-target is not used). Visual confirmation of selection is provided by highlighting the selected box and drawing a red disk centered at the mean fixation position with radius equal to the standard deviation of fixation points collected during the fixation. This feedback is shown in Figure 1 following selection of the central home position box.

The fisheye view is shown in Figure 2. The lens magni-

a. Schematic configuration. *c. Typical use.*
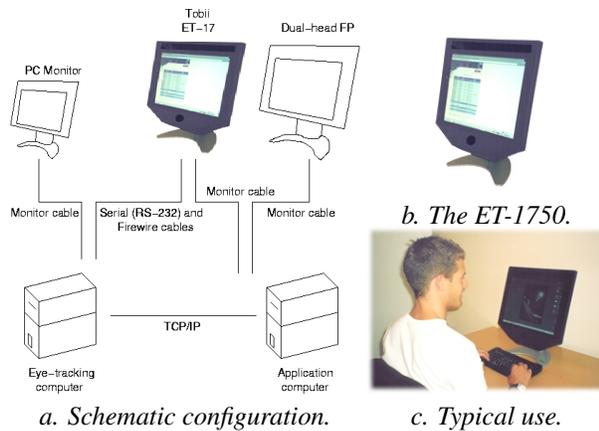
b. The ET-1750.

Figure 3: Tobii eye tracking hardware setup.

fication factor is fixed at 3. To keep the study parameters tractable, the scale of magnification was chosen arbitrarily to provide "reasonable" magnification—a factor of 1 would provide no magnification and higher factors may excessively distort the underlying imagery.

To alleviate the Gutwin effect during gaze-contingent lens movement, with the exception of the GHA fisheye, lens movement is attenuated in display space by a factor proportional to the inverse of the magnification factor at the measured gaze point within the lens. That is, when gaze falls within the foveal region, lens movement is attenuated by a factor of 1/3. When gaze falls outside the foveal region into the lens shoulder, motion is scaled proportionately to the magnification factor found at that location. The effect of this position-dependent control gain attenuation is mapping of the lens motion to data or screen space thus scaling ocular motion gain to that of the control condition.

Except for the Omnipresent condition, the fisheye is morphed into view in 400 ms, its appearance beginning 100 ms following fixation detection. The lens is in full view 500 ms after fixation detection.

3.4 Apparatus

Eye tracking is provided by the Tobii ET-1750 eye tracker. The Tobii is a 1280×1024 TFT flat panel monitor integrated with eye tracking optics capable of binocular tracking at $0.5°$ accuracy sampling at 50 Hz. A Pentium 4 PC running Windows XP and Tobii software delivers gaze coordinates via a TCP/IP connection. The TFT of the Tobii is driven by a dual-processor PC running Red-Hat Linux. The Linux PC receives real-time gaze data via the TCP/IP connection over a 100 Mbit LAN. The apparatus setup is schematically shown in Figure 3. Custom software linking Idelix Software's PDT library runs on the Linux PC, managing the gaze-contingent fisheye and

data collection facilities. Real-time fixation detection is performed by a fixation function for which source code is publicly available from LC Technologies, Inc. [15].

3.5 Subjects

13 subjects participated in the study (7 male, 6 female), with average age of 25. Subjects were screened for 20/20 (corrected) vision. Of the 13 participants, 4 did not complete the study, e.g., deeming the task too difficult. To assure analysis of complete data, incomplete recordings from these 4 subjects were deleted. Complete data from the remaining 9 subjects yielded a total of 1440 trials.

3.6 Procedures

Participants were seated 50 cm from the display and were familiarized with the user interface and with the relevance of the graphical feedback elements (gaze dot and translucent camera eye disks). To avoid potential "biofeedback", subjects were instructed to select targets by gazing at the target center and not at the fixation dot. It was explained that the fixation dot may be used peripherally to adjust one's gaze for target selection when, due to eye tracker error, the fixation dot does not coincide perfectly with perceived gaze direction.

A 9-point eye tracker calibration sequence was used to calibrate the eye tracker to each subject, patterned after Tobii's calibration program included in their commercial software ClearView [24]. A calibration point was redrawn and resampled automatically if validity data returned by the eye tracker was below threshold, defined as a deviation of not more than 1/50th of the screen's dimension along either the *x*- or *y*-axes.

3.7 Task

Following calibration, each subject completed 4 blocks of 40 trials. Odd numbered trials required the participant to fixate the central home position box. Even numbered trials required the participant to search for and select a randomly chosen target from the remaining 80 target boxes (excluding the central target).

Erroneous selections were permitted and logged when a participant aborted selection of the given target (this occurred occasionally when the eye tracker prevented acquisition of a target, e.g., at grid extremities). Following such an abort, the trial was restarted with a new randomly chosen target to allow collection of complete data for comparison.

Prior to each block of trials, subjects were given five practice trials in each input mode for familiarization with the selection technique.

4 Results

Data was collected from each subject's performance of 160 total trials and grouped (pooled) per fisheye condi-
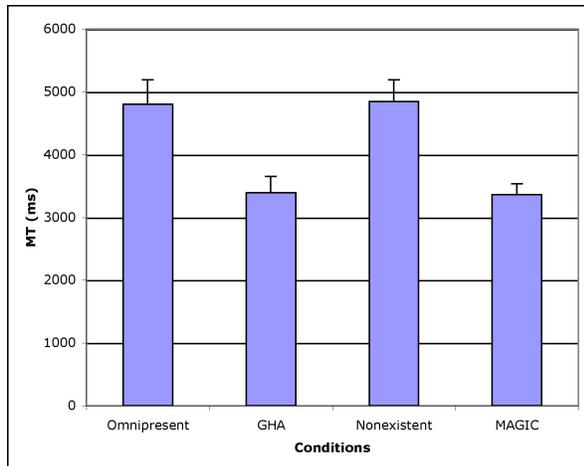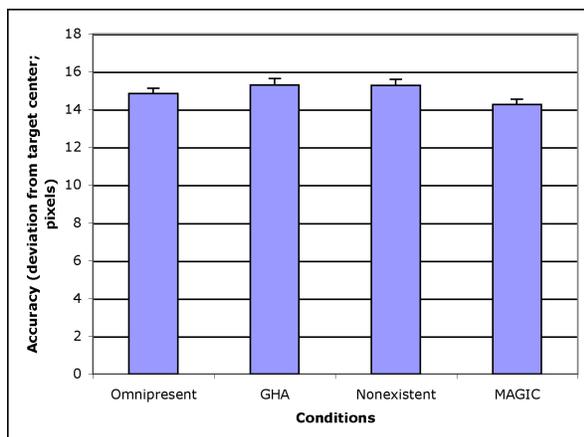
Figure 4: Mean selection time (MT).

Figure 5: Mean targeting error (ME).

Fisheye	MT (ms) (SE)	ME (pixels) (SE)
Nonexistent	4846.25 (346.92)	15.26 ∝ 0.46° (0.33)
Omnipresent	4801.40 (390.28)	14.84 ∝ 0.45° (0.28)
MAGIC	3359.48 (172.44)	14.26 ∝ 0.43° (0.30)
GHA	3393.38 (256.20)	15.30 ∝ 0.46° (0.33)

Table 1: Speed (MT, in ms) and accuracy (ME, in pixels and degree visual angle) measures with standard error (SE).

tion. Incorrect, or aborted, trials (selection of wrong target box) were not used in the speed/accuracy analysis. Of the 360 correct trials under each of the 4 conditions performed by all 9 subjects, the frequency of incorrect trials is as follows: Omnipresent = 48/408 (12%), Nonexistent = 62/424 (15%), MAGIC = 78/438 (18%), GHA = 106/466 (23%). With average abort rate of 17% (SD = 5%), descriptive statistics indicate no significant difference in abort rate between conditions.

4.1 Speed

Mean selection time (MT; in milliseconds) of subject data pooled per fisheye condition is given in Table 1 with standard error (SE). A standard weighted-means, one-way ANOVA of correlated samples was performed to examine the main effect of different fisheye conditions. The main effect (fisheye) is significant, $F(3,1436) = 7.8407$, $p < 0.0001$. Post-hoc Tukey HSD pairwise comparisons

(HSD[.05] = 1088.41, HSD[.01] = 1319.59; HSD[α] is the absolute difference between any two means required for significance at level α) revealed significant differences between the Omnipresent condition and both GHA and MAGIC conditions ($p < 0.01$) but not the Nonexistent condition. A significant difference was also found between the GHA and Nonexistent conditions ($p < 0.01$) and between the Nonexistent and MAGIC conditions ($p < 0.01$). Differences between mean completion times are shown graphically in Figure 4 with error bars indicating standard error (SE). The GHA and MAGIC conditions provide the fastest performance, with neither significantly better than the other. The Omnipresent and Nonexistent conditions provide the slowest performance and are not significantly different from each other.

4.2 Accuracy

Mean targeting error (ME; in pixels), measured as deviation from center of target, of subject data pooled per fisheye condition is given in Table 1 with standard error (SE). A standard weighted-means, one-way ANOVA of correlated samples was performed to examine the main effect of different fisheye conditions. The main effect (fisheye) is significant, $F(3,1436) = 5.5916$, $p < 0.001$. Post-hoc Tukey HSD pairwise comparisons (HSD[.05] = 0.75, HSD[.01] = 0.91) revealed significant differences between the GHA and MAGIC conditions ($p < 0.01$) and between the Nonexistent and MAGIC conditions ($p < 0.01$). Accuracy differences are shown graphically in Figure 5 with error bars indicating standard error (SE). The MAGIC and Omnipresent conditions provide the best accuracy, with neither significantly better than the other. The GHA and Nonexistent conditions provide the worst accuracy and are not significantly different from each other.

5 Discussion

Speed measures indicate that both the GHA and MAGIC lenses led to significantly faster target selection than with no fisheye or with a fisheye always slaved to the user's gaze. The most likely reason for this outcome is that both lenses provide the viewer with preview benefit when con-

ducting visual search for the target. This is because the user's visual field is not obstructed by the fisheye during the visual search portion of the task. In contrast, the Omnipresent lens sufficiently impedes visual search to negate any benefit offered by target expansion.

Accuracy measures suggest that the GHA lens interferes in some way with the selection task. Of the three lenses, only the GHA fisheye holds the lens at a fixed location after fixation onset. Where the central region of the lens lands is thus dependent on the user's first fixation. If the user's initial accuracy is poor, the target may appear distorted in the shoulder of the lens. Repositioning of the GHA lens requires a refixation. We observed most users preferred not to reposition the lens through refixation and opted to attempt selection of the distorted target in the lens shoulder. As a result, the misplaced lens negated any target width expansion benefits. Thus, although the GHA lens may offer a speed benefit during visual search (by virtue of being absent), if fixed off target, it hinders target selection. In contrast, both Omnipresent and MAGIC lenses improved selection accuracy by allowing interactive (eye-slaved) repositioning of the lens center.

We note two caveats regarding the interpretation of accuracy:

1. Because the time metric measures the combined search and selection task, the error metric is a rough indication of additional time needed to make a selection following search. It is, however, impossible to distinguish the precise amount of time that search consumed prior to selection.

2. Targeting error is close to what was expected: about 15 pixels, on average. However, the difference in error between the conditions, over all trials, is significant. This simply suggests that the Nonexistent and GHA conditions pose more difficulty for target selection than the other two conditions. This is not surprising since in these conditions the inherent difficulty of eye pointing surfaces.

Although we did not collect users' subjective impressions, we report two poignant remarks made by two users:

1. When faced with the Nonexistent lens condition as the last experimental task block (as dictated by the Latin square), one user refused to go on further claiming the task too difficult.

2. When using the Omnipresent fisheye (prior to exposure to the other fisheyes) another user noted that he had trouble previewing the target grid and asked whether the fisheye could be taken away for the purpose of "scanning the target field".

These two points are rather indicative of the benefit of the MAGIC lens for both speed and accuracy. During target search, the potentially distracting distortion of the MAGIC fisheye is hidden from view and does not impede visual search. Once the target has been located, the magnification of the MAGIC fisheye aids in target selection.

6 Conclusion and Future Work

This paper introduced a refinement to eye pointing with a fisheye lens. By simply hiding the lens during visual search, the user maintains an overview of the desktop while zooming in on the foveal region of interest. We have shown that this style of interaction leads to improvement in speed and accuracy over eye pointing with no fisheye or with a fisheye that is always slaved to the user's gaze.

Our study extends eye pointing research by considering visual search as a precursor to the Fitts' Law eye pointing task. Our results support Miniotas et al.'s [21] earlier work indicating eye pointing improvement by target expansion and suggest several potential application areas. First, applications involving visual inspection may be aided by the provision of a magnifying fisheye lens. Visual inspection applications include examination of imagery ranging from poultry, meat, and fish, to drug inspection, to medical X-ray inspection, to production line inspection, and to photo interpretation, to name a few [23, 14]. Second, the fisheye display constitutes a novel experimental paradigm for basic vision research: the magnified moving window. This variant of the moving window paradigm pioneered by McConkie and Rayner [17] may lead to novel insights in reading studies.

Finally, endowing the gaze-contingent fisheye with robust interaction controls has the potential for novel Attentive User Interfaces. Controls for manipulating lens characteristics (e.g., zoom factor, shape, visibility, etc.) can be offered to the user. Direct manipulation of the lens with the eye, however, may be difficult. As Fono and Vertegaal [7] suggest (and as Zhai et al. did as well [29]), a potential solution to interactive control of the gaze-contingent fisheye may involve a combination of ocular and manual inputs. For example, the fisheye could appear following fixation detection, as our MAGIC and GHA lenses did, then be made to disappear with a keystroke. For disabled users, a glance to an off-screen target could be used instead.

References

[1] Applied Science Laboratories, URL: <http://www.-a-s-l.com/definitions.htm>. *Technology and Systems for Eye Tracking*, 2004. Last accessed 12/10/04.

[2] R. Bates and H. Istance. Zooming Interfaces!: Enhancing the Performance of Eye Controlled Pointing Devices. In *Proc. Assistive Technologies*, pages 119–126. ACM Press, 2002.

[3] P. Baudisch, N. Good, V. Bellotti, and P. Schraedley. Keeping Things in Context: A Comparative Evaluation of Focus Plus Context Screens, Overviews, and Zooming. In *Proc. CHI '02*, pages 259–266. ACM Press, 2002.

[4] M. S. T. Carpendale, D. J. Cowperthwaite, and F. D. Fracchia. 3-dimensional pliable surfaces: For the effective presentation of visual information. In *Proc. UIST '95*, pages 217–226. ACM Press, 1995.

[5] A. T. Duchowski. *Eye Tracking Methodology: Theory & Practice*. Springer-Verlag, Inc., London, UK, 2003.

[6] A. T. Duchowski, N. Cournia, B. Cumming, D. McCallum, A. K. Gramopadhye, J. S. Greenstein, S. Sadasivan, and R. A. Tyrrell. Visual Deictic Reference in a Collaborative Virtual Environment. In *In Proc. ETRA '04*, pages 35–40. ACM, 2004.

[7] D. Fono and R. Vertegaal. EyeWindows: Evaluation of Eye-Controlled Zooming Windows for Focus Selection. In *Proc. CHI '05*. ACM Press, 2005.

[8] H. H. Greene and K. Rayner. Eye Movements and Familiarity Effects in Visual Search. *Vision Research*, 41(27):3763–3773, 2001.

[9] C. Gutwin. Improving Focus Targeting in Interactive Fisheye Views. In *Proc. CHI '02*, pages 267–274. ACM Press, 2002.

[10] C. Gutwin and A. Skopik. Fisheyes are Good for Large Steering Tasks. In *Proc. CHI '03*, pages 201–208. ACM Press, 2003.

[11] A. J. Hornof and A. Cavender. EyeDraw: Enabling Children with Severe Motor Impairments to Draw with Their Eyes. In *Proc. CHI '05*. ACM Press, 2005.

[12] R. J. K. Jacob. What You Look at is What You Get: Eye Movement-Based Interaction Techniques. In *Proc. CHI '90*, pages 11–18. ACM Press, 1990.

[13] Q. Ji, H. Wechsler, A. T. Duchowski, and M. Flickner. Editorial, Special Issue on Eye Detection and Tracking. *Computer Vision and Image Understanding*, 98(1), 2005.

[14] H. L. Kundel and P. S. LaFollette. Visual Search Patterns and Experience with Radiological Images. *Radiology*, 103:523–528, 1972.

[15] LC Technologies, URL: <http://www.eyegaze.-com>. *The Eyegaze Analysis System*, 2004. Last accessed 12/10/04.

[16] P. Majaranta and K.-J. Raiha. Twenty Years of Eye Typing: Systems and Design Issues. In *Proc. ETRA '02*. ACM Press, 2002.

[17] G. W. McConkie and K. Rayner. The Span of the Effective Stimulus During a Fixation in Reading. *Perception & Psychophysics*, 17:578–586, 1975.

[18] M. McGuffin and R. Balakrishnan. Acquisition of Expanding Targets. In *Proc. CHI '02*, pages 57–64. ACM Press, 2002.

[19] D. Miniotas. Application of Fitts' Law to Eye Gaze Interaction. In *Proc. CHI '00 Extended Abstracts*, pages 339–340. ACM Press, 2000.

[20] D. Miniotas and O. Špakov. An Algorithm to Counteract Eye Jitter in Gaze-Controlled Interfaces. *Information Technology and Control*, 1(30):65–68, 2004.

[21] D. Miniotas, O. Špakov, and I. Scott MacKenzie. Eye Gaze Interaction with Expanding Targets. In *Proc. CHI '04*, pages 1255–1258. ACM Press, 2004.

[22] J. B. Pelz, R. Canosa, and J. Babcock. Extended Tasks Elicit Complex Eye Movement Patterns. In *Proc. ETRA '00*, pages 37–43. ACM Press, 2000.

[23] J. W. Schoonard, J. D. Gould, and L. A. Miller. Studies of Visual Inspection. *Ergonomics*, 16(4):365–379, 1973.

[24] Tobii Technology AB. Tobii ET-17 Eye-tracker Product Description (v1.1), 2003.

[25] R. Vertegaal. Attentive User Interfaces (Editorial, Special Issue on Attentive User Interfaces). *Comm. of the ACM*, 46(3), 2003.

[26] R. Vertegaal. Method and Apparatus for Communication Between Humans and Devices. US Patent Application No. 2004-0183749-A1, 23 September 2004.

[27] C. Ware and H. H. Mikaelian. An Evaluation of an Eye Tracker as a Device for Computer Input. In *Proc. CHI/GI '87*, pages 183–188. ACM Press, 1987.

[28] S. Zhai, S. Conversy, M. Beaudouin-Lafon, and Yves Guiard. Human On-line Response to Target Expansion. In *Proc CHI '03*, volume 5, pages 177–184. ACM Press, 2003.

[29] S. Zhai, C. Morimoto, and S. Ihde. Manual and Gaze Input Cascaded (MAGIC) Pointing. In *Proc. CHI '99*, pages 246–253. ACM Press, 1999.