

Hidden in Plain Sight: an Exploration of a Visual Language for Near-Eye Out-of-Focus Displays in the Peripheral View

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ABSTRACT

In this paper, we set out to find what encompasses an appropriate visual language for information presented on near-eye out-of-focus displays. These displays are positioned in a user's peripheral view, very near to the user's eyes, for example on the inside of the temples of a pair of glasses. We explored the usable display area, the role of spatial and retinal variables, and the influence of motion and interaction for such a language. Our findings show that a usable visual language can be accomplished by limiting the possible shapes and by making clever use of orientation and meaningful motion. We found that especially motion is very important to improve perception and comprehension of what is being displayed on near-eye out-of-focus displays, and that perception is further improved if direct interaction with the content is allowed.

Author Keywords

peripheral view; near-eye displays; visual language

ACM Classification Keywords

H.5.m. Information Interfaces and Presentation (e.g. HCI): User Interfaces.

General Terms

Performance; Experimentation; Design; Human Factor.

INTRODUCTION

Our peripheral view provides us with a wealth of information without having to shift the focus of our eyes. It is a mechanism that informs us of things that are happening in our surroundings and that attracts our attention to certain events. The peripheral view has been widely explored as an additional information channel for large screen displays, mostly to raise awareness of particular situations, for instance during collaborative work [4], and as 'glanceable' information sources to

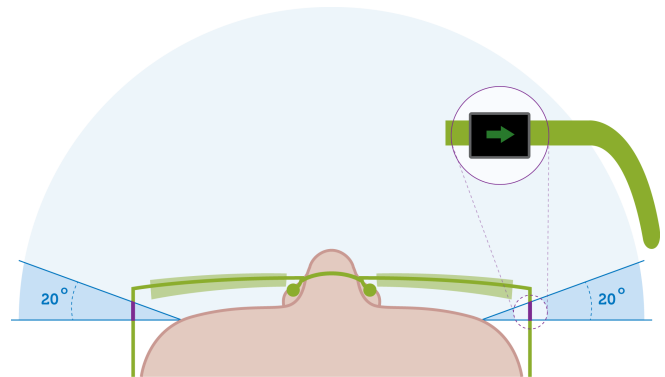


Figure 1. Top view of peripheral displays inside a pair of glasses (indicated by the purple lines along the temples), and the corresponding periphery, which is a field of about 180°. The displays are located near the border of the eyes, within the 20° extremes of our periphery. The call-out shows a concept drawing of a tiny display that is attached to the leg of the glasses.

trigger opportunistic interactions [17]. One of the often cited benefits, is the relatively low cognitive cost of using the peripheral view. Users do not have to shift their focus away from their task at hand and can continue that task while absorbing the peripheral information. Some literature refers to these displays as *ambient displays*.

One type of peripheral display is an *intimate display*, a display that has a close one-to-one relationship to the user and is solely intended to present information to that one user. We investigate one particular type of intimate peripheral display, which presents visual information *very close to the eyes* of the user. Our setup resembles the approach taken by Costanza et al. for eye-q [6], where two near-eye displays are embedded into eyeglasses to deliver discrete, unobtrusive and subtle cues to the user. However, eye-q has a limited resolution, with only eight single color pixels (four red and four green LEDs) on each side. We are interested in using near-eye displays with a higher resolution: we explore the amount of information that can be transferred using actual LCD displays in the peripheral view.

A consequence of using near-eye peripheral displays, is that our eyes cannot clearly focus on them due to their location. Our perception of the graphical elements shown on the dis-

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plays will thus be blurry. This contrasts most of the peripheral display approaches, which require a three-step process from the user: (1) awareness is triggered by a cue presented on a peripheral display, (2) the user evaluates whether a shift in focus is needed based on the changes perceived in the peripheral view, and (3) the user shifts focus and as a result the information moves from the peripheral to the foveal vision. We label approaches that follow these steps as *focus-shift interfaces*.

Similar to near-eye display approaches such as eye-q [6], we aim for information transfer of visual data without an explicit shift in focus. Presenting graphical elements to users in their peripheral view, at a location on which the eyes cannot focus, might seem contradictory, since when consuming visual content that interests us, we usually explicitly shift our focus to the content and then interpret it. Our goal, however, is to make use of the part of our vision that lies outside the region of focus, at the boundaries of our periphery, but where some information transfer of visual data can still be accomplished. Heun et al. [9] provide a comprehensive overview on the interplay between focus (foveal view) and peripheral vision.

Figure 1 presents a top view of the envisioned setup, depicting the whole visual field or periphery, which is a bit over 180°, and the location of the peripheral displays. Because the displays are located very close to the eyes, they can be very small, so that they fit on the insides of the temples of a pair of glasses.

In this paper, we make the following contributions:

- We explore the suitability of high-resolution near-eye displays to present graphical elements in the peripheral view, outside of the user's focus. We map the usable area of the displays and show that displays of limited size suffice, so they can be embedded into a regular pair of glasses.
- We develop the *basic graphical elements for a visual language* to present information on near-eye out-of-focus peripheral displays.
- We determine the suitability of such displays for interactive control and assess the precision of interaction.

To this end, we perform a three-stage user study. The results show that users can only perceive shapes to a limited extent on near-eye peripheral displays without shifting focus, and that orientation and motion are highly important to emphasize the meaning of a shape. With the findings presented in this paper, effective interfaces for intimate displays outside of the user's focus can be created. Such interfaces can support tasks that require continuous (visual and cognitive) focus by providing additional information that does not interrupt the task's execution.

MOTIVATION AND ILLUSTRATIVE SCENARIOS

One can easily imagine many interesting situations in which intimate, near-eye peripheral displays are valuable. However, this paper does not focus on developing a set of practical applications, but rather on exploring the visual design space for this kind of displays. Our primary goal is to thoroughly investigate the information transfer that can be achieved with such

displays, and in particular with displays that use regular display technology and that are located in a place that prohibits our eyes to clearly focus on them. We believe that an in-depth exploration of a suitable *visual language* is a prerequisite to develop effective peripheral visualizations.

Although the focus of our work is on the underlying visual language, and not on building specific applications, we do discuss some illustrative scenarios that highlight the potential use of near-eye peripheral displays in this section. These scenarios show a clear contrast with using a mobile device such as a smartphone or smartwatch that requires a shift of attention. Users often refrain from explicitly consulting their mobile device for information, either due to the social context (e.g. it might lead to an awkward social situation), environmental and safety issues (e.g. reaching for a mobile device might result in an unsafe situation, or it might be dangerous to shift focus to the screen of a mobile device), or due to privacy concerns (e.g. sensitive information might be revealed to others). Besides the possibility to provide subtle and personal notifications, the scenarios also show how such displays can be used to improve task performance by getting information directly across to the user rather than through focus-shift interfaces.

Driving and Parking Assistance

A peripheral display is useful to guide drivers and to make them aware of information for which they otherwise have to shift their focus. Some car types already include a HUD (head-up display, a transparent display on top of the dashboard) to show essential driving information such as speed. This ensures that the driver does not have to move focus away from the road. Even with a HUD, a slight shift in focus is still required, but the road remains in the periphery, and thus the driver remains more aware of the surroundings.

With a near-eye peripheral display, additional information can be provided to a driver without any shift in focus. The display can easily show, for example, that a car is fast approaching from behind, whether the speed limit is reached or exceeded, or parking sensor data that indicates how close the car is to surrounding objects.

Public Speaking

Novel presentation and public speaking tools that use smart glasses and augmented reality, such as Logue [7] and Rhema [23], are convenient in that they provide feedback to the speaker in an intimate and subtle way. However, this feedback still requires the speaker to shift focus and interpret the information being displayed, which is often interrupting and might even require a shift in context. While we are in agreement with the overall goals of this kind of work, we believe these systems would benefit from using the peripheral view to inform speakers about their performance without interrupting them.

RELATED WORK

In addition to what our eyes are focusing on in the foveal view, we also receive visual information from the peripheral view, as it is part of our visual field. The visual field defines the range that we can see when our gaze is fixed at a certain

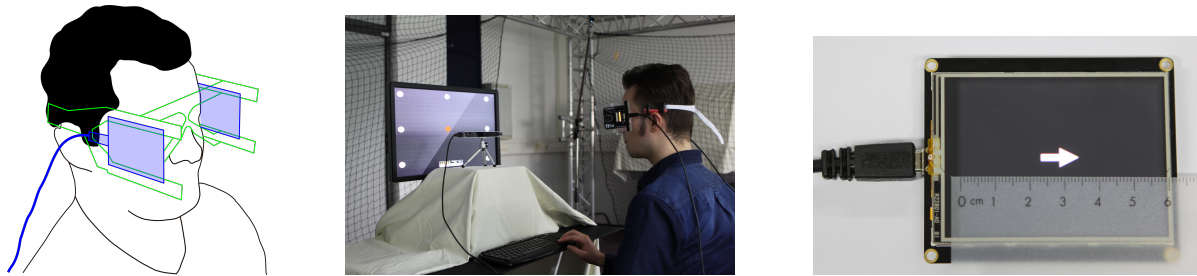


Figure 2. **Left:** experimental setup of glasses with peripheral displays used during our study. The near-eye out-of-focus peripheral displays were used to determine the usable display space, planar and retinal variables, and perception of motion. **Middle:** a participant wearing the glasses while sitting in front of an eye tracker. **Right:** closeup of a RoboPeak display that shows an arrow (same size as in the study).

point [24]. While we can only focus on about 3° of our visual range, the full range of visual information is a bit more than 180° [11]. However, since the acuity of the eyes falls back rapidly with increasing distance from the focal point, the size of objects that can be noticed and recognized needs to be almost exponentially bigger when further away from the focal point [1]. We counter this by placing peripheral displays very close to a user's eyes, so the user perceives the graphical elements on the displays as very large.

Research on peripheral displays has been going on since the sixties. Holden tested a peripheral vision horizon display (PVHD) for pilots [10], as did Keston, Doxtader and Massa [12]. Peripheral displays are interesting for complex tasks such as flying a plane, since it allows the pilot to stay aware of certain information without shifting focus away from the ongoing task. Peripheral displays thus avoid unnecessary interruptions that might have an effect on the performance of the task at hand. Hameluck and Stager wrote a review on PVHDs [8], in which they discuss PHVDs that attempt to provide the pilot with useful orientation data without the requirement to look directly at the information source. Interestingly, even over the course of 20 years of PVHD development, they state that “*the original theoretical basis of the PVHD as a compelling and automatic orientation stimulus appears to be questionable, the PVHD concept merits further more carefully controlled evaluation*”.

Although a vast amount of literature on the topic of peripheral displays exists [4, 8, 14, 15, 16, 19, 20, 22], the majority is about displays at a distance that allow glancing and focus shifting. Our work is in many ways the opposite of this kind of work. For example, in their work on managing user attention in peripheral displays, Matthews et al. emphasize the need for a three-stage model, similar to the so-called focus-shift interfaces, that first notifies the user, then tries to accomplish an appropriate transition toward the content on the peripheral display, after which the user has a more detailed view (due to a change of focus) of the content [18]. Our goal is to avoid the need for a transition, so the eyes can maintain their focus on the task at hand. In addition, Matthews et al. and Pedersen and Sokolor [21] discuss the need of abstraction of the visual information. Indeed, our study shows that for near-eye peripheral displays a high degree of abstraction is required, as details are very hard to perceive by the user.

There are also many theories and models regarding the perceptual recognition of objects on which the eyes can focus, such as recognition-by-components or RBC [3]. However, these theories and models are often not usable for near-eye out-of-focus displays, which are situated in the extreme regions: (1) only a few millimeters away from the eyes, which leads to a blurred perception of the graphical elements shown on the display, and (2) in the extreme peripheral range, within a 20° range on both sides, as depicted in Figure 1. With respect to what type of visual language is suitable for peripheral displays, Maglio et al. provide some valuable insights [15]. They report that motion in the periphery is useful to notify a user that content is updated, while continuous motion can be distracting. We argue that motion, when it adds semantics consistent with the graphical element, is essential for gaining a better understanding of the information presented on near-eye peripheral displays. Moreover, slow or smooth motion can help to prevent unwanted distraction by a peripheral display [22].

As pointed out in the introduction, notable work on near-eye displays is eye-q [6], which is comparable to our work in setup and overall goals: enabling subtle, intimate notifications through small displays located alongside the eyes. Costanza et al. show that intimate displays are suitable to provide simple yet strong cues that guide and instruct users. Due to the limited set of pixels (four red and four green pixels on each side), they can only offer a fairly restricted set of cues or instructions. This motivates us to explore a visual language that can be used for displaying information on near-eye displays that have a higher resolution.

A VISUAL LANGUAGE FOR PERIPHERAL NEAR-EYE OUT-OF-FOCUS DISPLAYS

Instead of developing a domain specific visual language, we focus on exploring the foundations of a visual language for peripheral near-eye out-of-focus displays, so that new visual languages can be build on top of this. More specifically, we explore the *planar* and *retinal variables* [2]. These variables make up the basic elements of a visual language.

The *planar variables* define the horizontal and vertical position where the graphical elements should be placed on the display. In our case, the planar variables should fall in the region alongside the eye where graphical elements are still perceivable by most if not all persons. For this purpose, we

explore the usable display area in the first stage of our user study.

The *retinal variables* are the set of basic properties that help the understanding when a graphical element is used in some kind of presentation. The retinal variables of a graphical element are: (1) shape, (2) size, (3) color, (4) brightness, (5) orientation and (6) texture. Given the position of the display, we can eliminate brightness and texture in our study. The brightness is fixed in our experiment: the display is not too bright to avoid blinding the user, and bright enough to make sure everything on the display is visible. In real-life conditions brightness would be heavily influenced by environmental light. This implies that brightness should not be used to convey information: it is perceived differently in different environmental conditions. Also detailed variations in texture would have a negative impact on visibility, because our eyes cannot see subtle contrasts and variations in color if the display is very close to the eye.

Besides the planar and retinal variables, we explore one additional aspect that plays a very important role in other peripheral displays: *moving* graphical elements. Movement is easy to observe and adds additional information to the elements being presented on a near-eye peripheral display. We deliberately avoid other types of dynamic elements like blinking and highlighting. Since we aim for subtle and non-distracting information transfer, more intense events in our peripheral view will attract our immediate attention or sometimes even trigger reflexes, which we want to avoid at all cost. In contrast, moving graphical elements can be done in a subtle and fluent way while avoiding to distract the user.

In our study, we mainly explore the recognizability of basic graphical elements. We deliberately want to avoid that users constantly try to shift their focus to see what is displayed in their peripheral view, so an important aspect of a visual language for peripheral displays is the ease with which its graphical elements are recognized. The human processor model [5] defines that a piece of information is first seen through our eyes, then processed through the perceptual processing pipeline, and finally goes through the cognitive processing pipeline where we make decisions based upon our evaluation of this information. For near-eye out-of-focus displays, the perceptual processing pipeline has to work with incomplete information, since the graphical elements are heavily blurred. This implies that a visual language for such displays should be optimized for visual recognizability rather than visual expressiveness or semiotic clarity. For example, although single digits and letters of an alphabet are simple graphical constructs, most if not all people are unable to recognize these on a near-eye out-of-focus display. Taking all of this into account, we focus our study on perceptual discriminability.

STUDY

To determine a visual language that is suitable for near-eye out-of-focus peripheral displays, we performed a user study in three different steps. First, we explored the *planar variables*, including the usable display area and the most suitable location and size for graphical elements. In a second stage,

we investigated the basic properties of the graphical elements that can be transferred, based on a subset of the *retinal variables*. We explored the effect of (composite) shape(s), orientation and the (combination of) color(s) on the perception of users. In our third and final stage, we explored the contribution of *motion* on the perception of users.

Apparatus

Our prototype, shown in Figure 2, consists of an acrylic glass structure in which two displays are mounted (RoboPeak¹ displays of 74 by 60 mm, with a resolution of 320 by 240 pixels), and is fitted out with small cushions and a strap to increase comfort. The displays are controlled over USB 2.0, using a laptop running Microsoft Windows 10. For rendering, we use Qt version 5.5 in combination with a custom developed authoring tool that allows us to select shapes and animations, and define how these have to be displayed on both screens (separately, mirrored, or inverted). To allow exploration of how to use near-eye out-of-focus displays, the displays we use for our study are much bigger than the display size that is actually required for rendering visuals that can be perceived by users.

During the first stage of our study, the prototype shown in Figure 2 (left) was used. For the second and third stage, the same prototype was used, but we also used an Eye Tribe eye tracker to monitor the gaze direction of the eyes of the participants. All experiments were conducted in a slightly darkened room to prevent direct light from reflecting on the glossy displays.

During the study, two observers were present. The first observer acted as an operator who controlled the content of the displays using the authoring tool, monitored the eye tracking data, and logged the participant's response times. A second observer took notes about the participants' answers. The experiments were also recorded on video (including audio) in case further analysis is required.

Methodology

We used a within subjects experimental design. In the first stage of our study, we investigated the *planar variables* by asking each participant to identify the *usable display area* in which they could perceive information on the display. To accomplish this goal, we used a scanning approach: participants had to indicate when they stopped noticing a red dot that was moved step by step. The red dot was iteratively moved 10 pixels forward (from ear to nose), and for each vertical position, it was moved up and down until the participant did no longer see the object. We performed this test for the left and right eye separately. Participants were asked to focus their eyes on a fixed spot straight ahead, at two meters distance. The results from this first stage provide us the usable display area. For the second and third stage, we constrained the screen space according to these findings.

In the second stage, we mapped the *retinal variables*. The participants were asked to identify shapes presented on the peripheral displays. Both displays always showed the same

¹http://www.robopeak.com/data/doc/rpusbdisp/RPUD01-rpusbdisp_datasheet-enUS.1.2.pdf

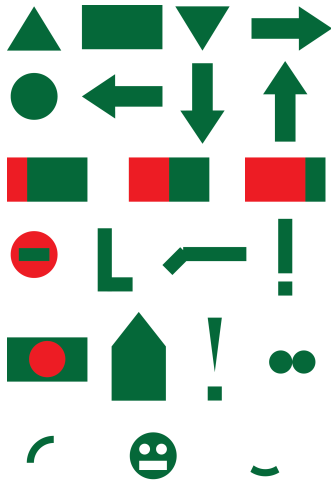


Figure 3. An overview of the static elements used during the second stage of our study. The set of graphical elements contains simple shapes, composite shapes, shapes with two different colors, and some more complex figures.

shape, which was positioned in the yellow area shown in Figure 5 to ensure it is inside the usable display area for all participants. As a first step, we asked the participants to recognize six colors (red, green, blue, yellow, purple, orange) and choose the color they considered to have the most contrast with the black background of the display. For each user, we identified the color that has most contrast with the chosen color (according to the traditional “theory of color”). This contrasting color is used during the study in visual elements composed of two colors.

Then, we showed a set of carefully selected shapes, shown in Figure 3, one by one in the chosen color. Some shapes were repeated multiple times. We asked the participants to describe in their own words, and as detailed as possible, what they thought they saw. As a last step of the second stage, we presented the same set of shapes to the participants. This time, however, we asked them to identify what they thought they saw using a printed reference sheet (a printed version of Figure 3) with all shapes that occur in the test.

An eye tracker was used to present real-time gaze feedback to the participants on an auxiliary monitor showing a grid of dots, with the one in focus (gaze) highlighted. This feedback helped participants to keep their focus fixated in front of them and keeping their gaze away from the peripheral displays. In addition, the eye tracking data was used to help participants avoid the (unconscious) urge to constantly glance at the peripheral displays before answering questions (a phenomenon called self-interruption [22]). It is impossible to truly fixate all eye movements [13] so glancing sometimes happens involuntarily, but it did not occur to an excessive degree during the study. Although the eye tracker provides some additional validation for the experiment, we believe it is not indispensable, as the displays are impossible to clearly focus on and a very sporadic quick glance is inevitable. Looking straight ahead while avoiding focus shifts approaches a worst case scenario, implying that results might even be better for real-life usage



Figure 4. An overview of the animated shapes (“motion”) used during the third stage of our study. Each row represents five frames from the animation (on the left the first frame, and on the right the last frame).

where our eyes often shift focus and accidentally glance in the direction of a peripheral display.

In the third and last stage, we presented the user with moving shapes to investigate how motion contributes to the perception and understanding of graphical elements on near-eye peripheral displays. We opted for *meaningful motion* rather than testing various motions in isolation. In other words, the movement of shapes should strengthen the perception and understanding of the graphical elements. For example, a graphical element representing an upward arrow also moves upward, a two-color bar is gradually filled with one color, and a clock-like graphical element has a rotating clock hand.

Figure 4 provides an overview of the moving graphical elements in our testset that were presented to the participants. We presented 20 moving elements to the participants, and again they had to describe what they thought they saw. Some graphical elements were repeated, but differed in the duration or extent of the motion. The movement repeated three times (e.g. an arrow made the same upward motion three times), unless the participant immediately recognized that which was displayed. Similar to the second stage, the eye tracker was used for feedback and validation.

In addition to studying the perception of motion, we also explored how precisely participants can interact when they are able to control the movement of a shape. We asked them to perform seven different interactive tasks, based on the animations that were shown before: (1) filling a bar up to 50%, (2) filling a bar up to 75%, (3) filling a bar up to 100%, (4) rotating a clock hand 180°, (5) rotating a clock hand 360°, (6) rotating a clock hand 540°, and (7) moving a circle on top of a square. Participants controlled the movement by pressing two keyboard keys.

Participants

In total, 18 persons (7 female, 11 male) participated in the study, but for practical reasons, not all of them took part in all

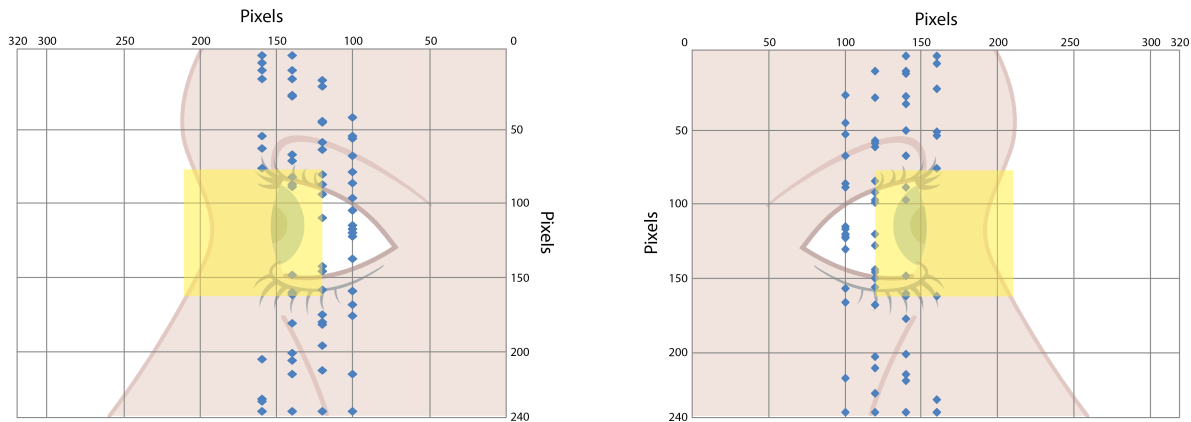


Figure 5. Side view of the usable display area for each eye. The outer rectangle represents the peripheral display, the yellow rectangle the screen space that we used during the next stages of the study. The dots present the aggregated results of the boundary of the viewable region. The rendering of the eye in the background is for illustrative purposes and does not reflect exact measurements.

three stages of the study. Each of the stages had 10 participants, and only 3 participants took part in all the stages. Participants' ages ranged between 19 and 37 years old, and 11 of them wear glasses on a daily basis. They could not wear their glasses during the study, but this was never an issue because the displays are very close to the eyes.

RESULTS OF THE STUDY

In this section, we present the results of the four stages of the user study.

Stage 1: Usable Display Area

Figure 5 presents the results of the first stage of the study: a side view of the usable display area for each eye. The dots indicate where on the display the red dot that was shown during the study was no longer visible, aggregated for all participants. The yellow rectangle indicates the screen space we used in the second and third stage of our experiment, falling well within the viewable range for practically all participants. The rectangle is a common denominator for usable display space. To the front, it is capped at the level of the nasal bone, since this is typically the horizontal range of a temple that can hold such displays. Although the shape of the eye undoubtedly plays a role in the usable display area, we expect the minimum range indicated here to be suitable for most if not all persons.

Stage 2: Retinal Variables

As a first part of the second stage of the study, we assessed the set of colors to use when rendering shapes. Participants were able to correctly perceive the primary screen colors (i.e. red, green and blue), while yellow, purple, and orange were correctly perceived by 8, 5 and 3 participants respectively. Yellow and orange were often confused, while purple was often interpreted as blue. Participants had to choose the color that they preferred in terms of contrast: 3 participants chose red, 3 green, 2 blue, 1 yellow and 1 orange.

Figure 6 presents the recognition rates for the static shapes that were shown to the participants without the use of the printed reference sheet that gave an overview of all shapes.

It indicates what shapes are recognizable on near-eye out-of-focus peripheral displays, and what shapes are hard to recognize. The order of the shapes in the graph is the same order as they were presented in to the participant. An answer was only rated as *correct* (shown in green in the graph) when the participant gave a completely correct answer, including the exact shape, orientation, and subcomponents in case of a more complex shape. An answer was rated as *partially correct* (shown in orange in the graph) when a participant answered with a shape that is generally considered as a similar shape (e.g. 'square' instead of 'rectangle') or with a shape that is a subpart of the shape that is shown (e.g. 'irregular vertical rectangle' instead of 'exclamation mark'). The rectangle recurred several times in each session, and interestingly was recognized with different, though similar, recognition rates. Even for basic shapes, participants were somewhat uncertain about what they perceived. Note, however, that the fairly common answer 'square' was only counted as a partially correct answer.

Composite shapes (e.g. the iconic face, the exclamation marks, the house, or the arrows) are hard to recognize in detail. Surprisingly, for some composite shapes, orientation seems to matter: the upward and downward arrows have higher recognition rates than the backward and forward arrows (when presented on the peripheral displays, left arrows point forward for the user, and right arrows point backward).

For the classification task in which the participant can use a printed reference sheet with all possible shapes, the results are shown in Figure 7. The recognition rates clearly improve when the user is provided with a set of possibilities from which to choose. These results are not surprising, since the possibilities are much more constrained compared to the previous test, where the participant could answer whatever she or he thinks to perceive.

In terms of the retinal variables, we can conclude that composite shapes are of little use when the user is unaware of the set of possible shapes, since the recognition rates are low. As with composite shapes, using multiple colors does not improve recognition either. According to 8 participants, the col-

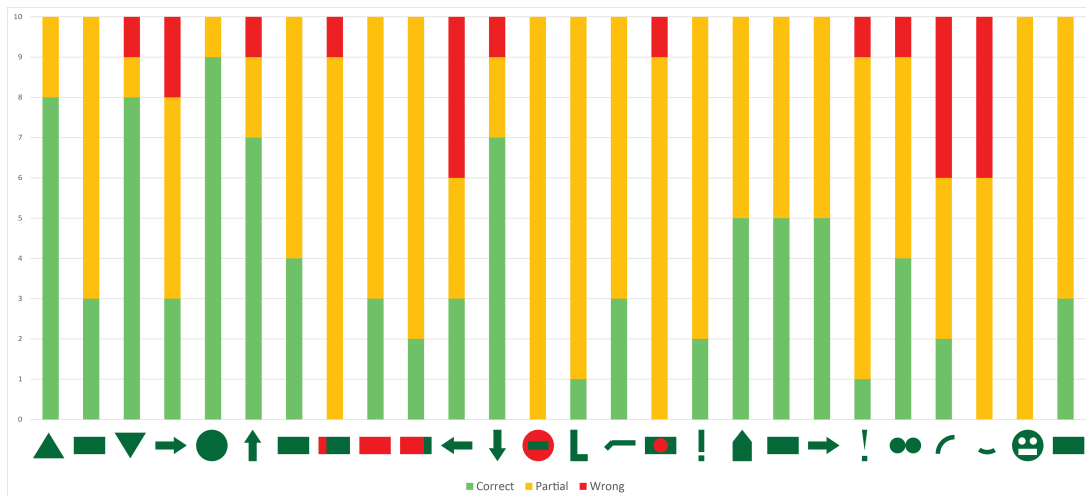


Figure 6. Recognition rates for static graphical elements without the use of a printed reference sheet.

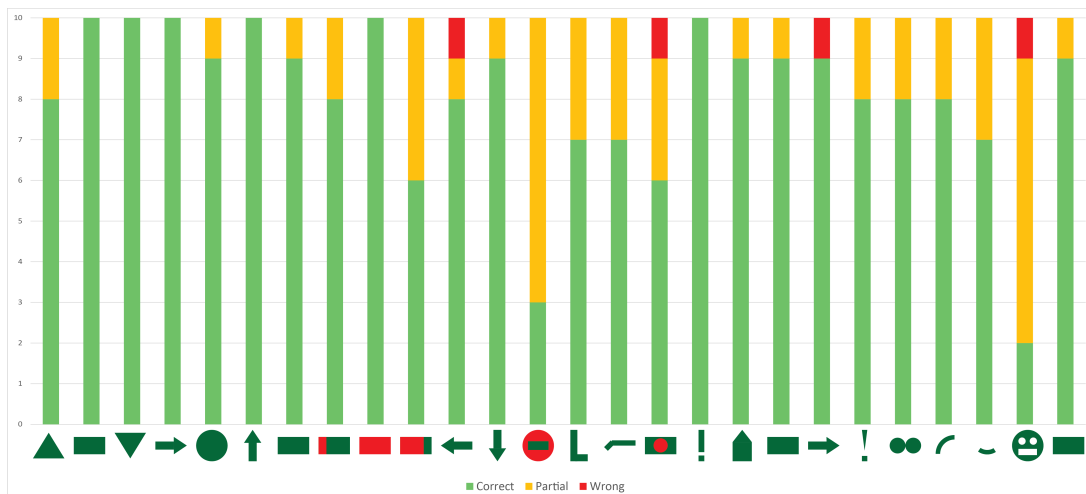


Figure 7. Recognition rates for static graphical elements when indicating the perceived shape on a printed reference sheet.

ors tend to be perceived as blending together which sometimes leads to shapes becoming more difficult to recognize or colors being misinterpreted. It seems that orientation does contribute to the perceivability of shapes, which is probably caused by the specificities of how our eyes work. Scanning imagery up-down (vertical orientation) is often easier than scanning imagery from close by to further away (horizontal orientation). Because the displays are very close to the eyes, when a shape is oriented horizontally, the projected change in distance from the eye seems much bigger than the actual change in distance from the eye.

Stage 3: Motion

Overall, participants performed very well when recognizing motion. Since we added meaningful movement to shapes, such as an arrow moving in the direction in which the arrow is pointing, we expected the movement to help in recognizing the shape. Figure 8 presents the recognition rates of movement paths or changes of shapes, while Figure 9 presents the recognition rates of the shape that is being animated. In both

graphs, it is clear that motion (and animation in general) is easily recognizable, while recognizing the shape that is being animated is not always easy. When the movement is very closely related to the meaning of a shape, the shape being moved is recognized correctly most of the times (e.g. the turning clock hand or the moving arrow). More complex visualizations (e.g. a circle moving on top of a square) or animations that involve two colors are generally hard to recognize.

We want to highlight that repeating animations improves the recognition rate, consistent with the findings of Matthews et al. [18]. As an animation was repeated up to three times, we noticed that the repetition often had a positive effect on recognition.

Stage 4: Interaction

In this final test, we allowed participants to control the visual elements shown in the peripheral view. Participants were instructed to move the visual elements using arrow keys. Interestingly, when participants were in control of the movement

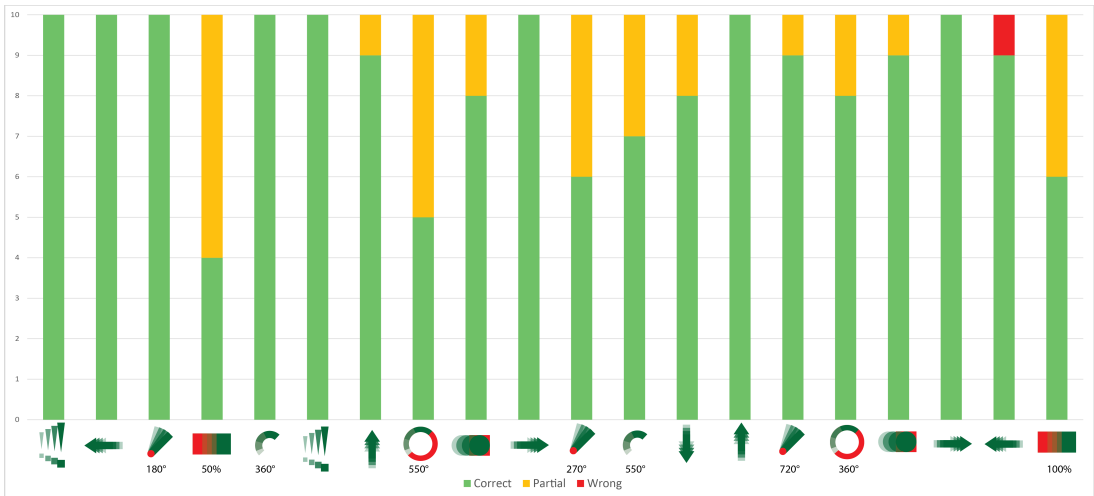


Figure 8. Recognition rates for the *path or change* of an animated shape.

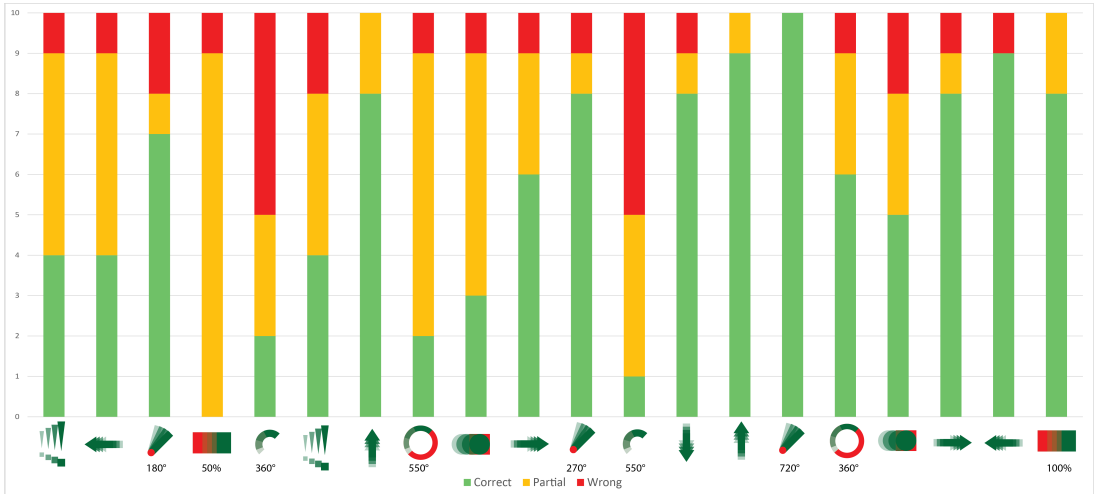


Figure 9. Recognition rates for what *shape* is being animated.

themselves, they were able to achieve a high degree of precision.

Figure 10 shows how participants performed when they were instructed to move the visual elements. The participants got four tasks: (1) filling a bar up to 50%, (2) filling a bar up to 75%, (3) filling a bar up to 100%, and (4) moving a circle on top of a square. Figure 11 show how participants performed for rotation tasks. The participants got three tasks to perform: (1) rotating a clock hand 180°, (2) rotating a clock hand 360°, and (3) rotating a clock hand 540°. We did not impose a time limit for these tasks and asked the participants to say “done” when she or he thought the task was accomplished.

It is clear from the box plots that when moving an object over a straight line to a given destination, participants often stopped on the target destination or just a few pixels away from the target. The same goes for rotating an object over a target angle. As expected, based on the results of previous tests, when participants had to control a movement involving two colors, the performance was worse. One exception

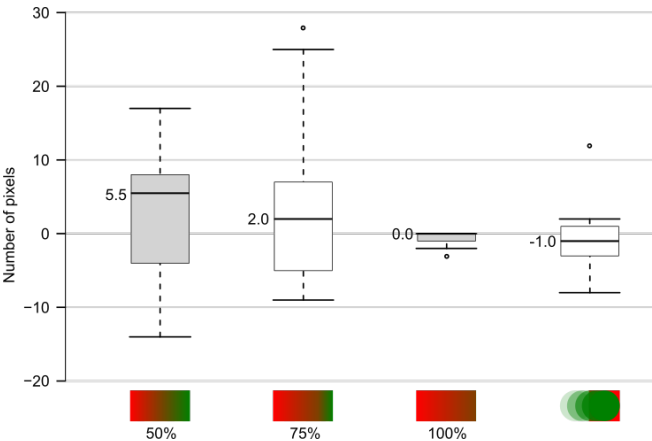


Figure 10. The precision of reaching a target (in pixels) for four different interactive tasks: (1) filling a bar up to 50%, (2) filling a bar up to 75%, (3) filling a bar up to 100%, and (4) moving a circle on top of a square. The vertical scale indicates the number of pixels.

was the task of filling a box completely with another color by pressing the keys (notice that participants could also overshoot in this task, to prevent the easy solution of just holding down the key for some time).

Moving a circle on top of a square was performed with good precision, which shows that these type of displays might be suitable for supporting, for example, communication of the available space left when parking a car. With respect to controlling the angle of a shape, we see that a bigger required change resulted in a lower precision. However, the maximum deviation was a 20° undershoot when a turn of 540° was required, which is still a limited deviation. In general, when rotating an object, participants tended to undershoot slightly, meaning that they turned the object over a somewhat smaller angle than required. In contrast, when moving an object across a path, participants tended to overshoot more often than undershoot.

DISCUSSION

The results of our study provide us with a set of simple yet effective guidelines when designing for near-eye out-of-focus displays. We formulate five easy-to-use guidelines that follow directly from the results of our study:

- (1) *Use simple shapes and avoid composite shapes.* Shapes that are composed out of multiple basic shapes, like ●● (two dots aligned) or ▲ (a triangle on top of a rectangle), are more difficult to recognize. When being displayed close to the eye, there is a blurring effect and adjacent shapes seem to blend, and are nearly impossible to distinguish.
- (2) *Use a single prominent shape.* Recognition rates are much better for shapes that use more pixels. Shapes that use fewer pixels are harder to recognize, despite the fact that the display is very close to the eye. For example, ◀ is much harder to recognize than ●.
- (3) *Use a limited set of predefined shapes.* Even with the extensive set of symbols we used during the study, the recognition rate turns out to be high (Figure 7) as long as the user knows beforehand what is included in the set of possible visualizations.
- (4) *Limit color usage to the three primary colors and strongly contrasting colors, and avoid composite colors.* When ex-

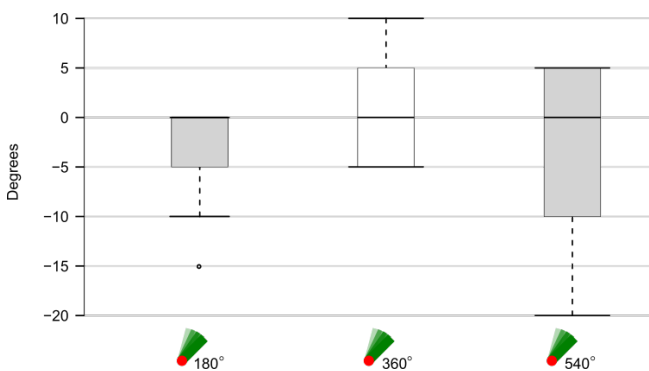


Figure 11. The precision of reaching a target (in degrees) for three different interactive tasks: (1) rotating a clock hand 180°, (2) rotating a clock hand 360°, and (3) rotating a clock hand 540°. The vertical scale is in degrees.

ploring the most visible color(s), all users could recognize the three primary colors. Users also did not have issues recognizing colors that are in strong contrast to the primary colors. However, using multiple colors in a (composite) shape does not aid the recognizability of what is being displayed.

(5) *Use motion to communicate additional complex information.* Our study shows that users are able to observe and interpret movements very well (the path or change, Figure 8), independently of the recognition of the shape. Figure 9 shows that a high recognition rate for the movement does not contribute to a better recognition of the shape that is being moved.

To illustrate these guidelines, we refer back to the illustrative scenario on *public speaking feedback*. We can now create appropriate designs for the real-time public speaking feedback system *Logue*, described in [7], using near-eye out-of-focus peripheral displays. To implement it, we use the library of the Logue system² that observes the speaker and outputs performance parameters. The library communicates three pieces of information: whether the user is speaking (1) too slowly or fast, (2) too loudly or softly, and (3) too energetically or subdued. Each of the indicators can be in one of three states: performing under, above or within acceptable levels. Following the guidelines above, these three pieces of information can be easily encoded as an appropriate visualization.

We use a combination of color, shape and motion to represent these distinct indicators and their states. First, a different color is assigned for pace (orange), volume (green) and energy (yellow). Our study shows that users can easily recognize these colors if they are not used at the same time (guideline 4). When the speaker is approaching the minimum or maximum threshold and might get out of range of the “acceptable level”, the visual representation of the corresponding indicator will appear, using scaling or a repetitive motion to indicate whether the minimum or maximum threshold is being reached (guideline 5). When the minimum threshold is crossed, the color of the shape will switch to blue to communicate this to the speaker. When the maximum threshold is crossed, the color will switch to red. In accordance with guideline 2, only a single shape is shown at once. When multiple indicators are approaching a threshold, the different indicator shapes will be shown one at a time for a limited period.

The shapes for the indicators are simple (guideline 1). The volume is represented by a triangle ▲ that grows when the speaker talks too loudly and shrinks when the speaker talks too quietly. Feedback about the pace is visualized with a vertically bouncing circle ●, bouncing fast when the speaker has to decrease the pace and slowly when the speaker has to increase the pace. The amount of energy in the movements of the speaker is also represented by a circle ●, but one that behaves similarly to the volume: the shape grows when the speaker is starting to behave too energetically and shrinks when the speaker is getting too subdued. Although the same shape is used for energy and pace, users can easily keep them apart because of the different color and motion. The shapes

²The Logue system is open source and available at <https://www.informatik.uni-augsburg.de/en/chairs/hcm/projects/tools/logue/>

only appear on the near-eye display when the speaker is approaching the minimum or maximum threshold. This way the speaker can adapt before reaching the threshold, thus maintaining an acceptable level of performance. Having this feedback available through the peripheral view has the advantage that speakers can keep eye contact with the audience while still being informed in real-time about their speaking performance. Furthermore, it is less disruptive, as the information is subtle and only shown when nearing one of the thresholds.

CONCLUSION

Based on the results of our study, it is clear that little can be achieved using only static shapes for near-eye out-of-focus displays. Even for simple shapes the recognition rate is low when a user without prior knowledge has to guess what shape is being presented. More complex (composite) shapes are even harder to recognize correctly. However, when the user is given a limited set of possible shapes beforehand, the recognition rate increases and even composite shapes have high recognition rates. When using a limited set of sufficiently different shapes (compared to the set we used in our study), the recognition rates will further improve. For communicating information such as a value in a range, our findings show that motion is a very effective tool. Especially interactive tasks, in which the user steers an object that is shown on the peripheral displays, were accomplished with great precision. Our exploration of a suitable visual language led to five design guidelines that can be used to create usable near-eye out-of-focus visualizations.

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